SCHOOL OF CIVIL ENGINEERING

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A STUDY OF THE DESIGN PARAMETERS FOR ASPHALT EMULSION TREATED MIXTURES

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PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

Interim Report

A STUDY OF THE DESIGN PARAMETERS FOR ASPHALT EMULSION TREATED MIXTURES

TO:	J. F. McLaughlin, Director Joint Highway Research Project	October 5, 1976
		Project: C-36-45M
FROM:	H. L. Michael, Associate Director Joint Highway Research Project	File: 6-18-12

The attached Interim Report "A Study of the Design Parameters for Asphalt Emulsion Treated Mixtures" by A. A. Gadallah, Graduate Instructor in Research on our staff, is presented on the HPR Part II Study titled "Design Parameters for Asphalt Treated Bases in Rigid and Flexible Pavement Systems". The Study and preparation of the Report have been directed by Professors E. J. Yoder and L. E. Wood of our staff.

This Report presents the findings of a detailed laboratory investigation of the effects of asphalt emulsion content, added moisture content, aggregate gradation and use of additives on the design parameters and properties of asphalt emulsion treated mixtures.

The Report is offered as partial fulfillment of the objectives of the Study and will be submitted to ISHC and FHWA for review and similar acceptance.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Associate Director

HLM:ms

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16. Abstract

This study reports the findings of a detailed laboratory investigation concerning the effect of asphalt emulsion content, added moisture content, aggregate gradation, and the use of additives (1% portland cement) on the design parameters and properties of asphalt emulsion treated mixtures (AETM) using Marshall Equipment. The evaluation was conducted at different curing stages of the mix. One aggregate type; and one asphalt emulsion type and grade were used in the study.

A modified Marshall method for preparing and testing AETM specimens was developed and used in the evaluation section of the study.

The evaluation of AETM properties resulted in a number of significant results. The properties of AETM are an outcome of a complex array of factors. Evaluating the mix properties as related to only a single factor is not sufficient; the interaction of these factors influence the properties of the AETM.

The study showed that Marshall Stiffness and/or Index could be used, in addition to the conventional design parameters for Marshall Method of mix design, to better control the mix properties.

The experiments showed that the water sensitivity test is very important in evaluating AETM properties and needs to be an integral part in the Marshall Design procedure for AETM.

Based on the results of the overall investigation, a recommended evaluation system for AETM was presented.

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Interim Report

A STUDY OF THE DESIGN PARAMETERS FOR ASPHALT EMULSION TREATED MIXTURES

by

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Graduate Instructor in Research

Joint Highway Research Project
Project No.: C-36-45M
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Prepared as Part of an Investigation

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in cooperation with the

Indiana State Highway Commission

and the

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Executive Summary

A STUDY OF THE DESIGN PARAMETERS FOR ASPHALT EMULSION TREATED MIXTURES

The study reports the findings of a detailed laboratory investigation concerning the effect of asphalt emulsion content, added moisture content, aggregate gradation, and the use of additives (1% portland cement) on the design parameters and properties of asphalt emulsion treated mixtures (AETM) using Marshall Equipment. One aggregate type; sand and gravel, and one asphalt emulsion type and grade were used in the study. The evaluation was conducted at different curing stages of the mix.

The Marshall equipment consisted of a mechanical compaction hammer and an autographic stability apparatus. The stability apparatus used in this investigation is essentially the same as the standard Marshall Equipment but it provides a continuous recording chart for the load (lbs.) versus deformation (0.01" units) throughout the testing range from which stability and flow values can be obtained.

The study consisted mainly of two major sections. The first section dealt with establishing a method for preparing and testing asphalt emulsion treated mixtures (AETM) using the Marshall equipment. The AETM were evaluated with emphasis on the coating, workability of the mix, ease of handling of the mix, curing rate and amount of moisture retained in the mixture before and after compaction. Based on these factors, a method for preparing the standard Marshall specimen was developed. In addition, a limited study was conducted to evaluate three different reported methods for water sensitivity tests in order to select an adequate method for AETM.

The second section of the study involved an evaluation of the influence of several factors on the performance of AETM. The predetermined methods of specimen preparation and testing procedures formed the basis for this investigation.

The evaluation of AETM properties produced a number of significant results. It must be recognized that the properties of AETM are an outcome of a complex array of factors. Evaluating the mix properties as related to only a single factor is not sufficient. The interaction of these factors influence the behavior and properties of the AETM and have to be considered in the evaluation.

The study showed that Marshall Stiffness (determined as the ratio between Marshall Stability and Flow, $S_m = \frac{P}{F}$) and/or Marshall Index (represented by the slope of the linear portion of the load-deformation trace obtained from the autographic Marshall Equipment) could be used, in addition to the conventional design parameters for Marshall method of mix design, to better control the mix properties by setting minimum values for these two parameters.

The experiments showed also that the water sensitivity tests have to be an integral part of the Marshall Design Procedure for AETM. Generally, high stability is obtained at the expense of lowered durability (measured here as the resistance to water damage) especially when using the unsoaked ("dry") Marshall stability trends in the design of AETM. The final design must provide a balance between stability and durability requirements. This would be achieved by controlling and evaluating both the "dry" and soaked properties of the mix with a greater emphasis on the soaked specimen results.

Based on the results of the overall investigation, an outline of the preparation and testing procedures for dry and soaked AETM specimens is presented as well as a recommended evaluation system for asphalt emulsion treated mixtures.

The results of this study serve several purposes. It provides the highway engineer with a better understanding of the influence of different factors on the design parameters and properties of asphalt emulsion treated mixtures using

Marshall equipment. Further, the results provide additional design parameters that could be used in conjunction with the conventional design parameters for Marshall method of mix design to better control the AETM properties. Finally, the laboratory preparation and testing procedures as well as the recommended evaluation system for AETM would provide an important and practical tool for the design of AETM using Marshall equipment.

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LIST OF SYMBOLS

AETM	-	Asphalt emulsion treated mixtures
%AE	-	Asphalt emulsion residue content, expressed as percent by weight of the dry aggregate
$\%V_A$	-	Percent air voids, excluding voids filled with moisture
F	-	Marshall Flow, measured at ≈ 72°F in 0.01" units
G_d	-	Dry bulk specific gravity of the AETM specimen
G_w	-	Wet bulk specific gravity of the AETM specimen
I_m	-	Marshall index
$\%I_m$	-	Percent retained Index after the water sensitivity test
%MA	-	Percent moisture absorption (moisture picked-up)
P	-	Marshall stability, measured at ≈72°F, in lbs.
%P	-	Percent retained stability after the water sensitivity test
S_m	-	Marshall stiffness = $\frac{P}{F}$
$\%S_m$	-	Percent retained stiffness
%TL	-	Percent total liquid at time of testing ($\%TL = \%AE + \%WC_o$)
$\%V_T$	-	Percent total voids = $\%V_A + \%V_w$
$\%V_W$	-	Percent of voids filled with moisture at time of testing
%W	-	Initial added moisture content, expressed as percent by weight of the dry aggregate
$\%WC_o$	-	Percent moisture retained in the sample at time of testing
γ_d	-	Dry unit weight of the sample in pcf
γ_w	-	Wet unit weight of the sample in pcf
VMA	-	Voids in mineral aggregate (based on the aggregate apparent specific gravity)

CHAPTER I: INTRODUCTION

As highway performance demands increased over the years, the importance of improving design methods and construction procedures of the different components of the pavement system have been recognized. Together with the increase of performance demands, the increased use of asphalt treated bases has made the design of the base material a critical factor.

An extensive study has been made of the performance of CRC pavements in Indiana (20)*. It has been demonstrated that the performance of asphalt bases beneath concrete pavements has, by and large, been successful, although, in recent years some distress has been noted on some of the heavily travelled roads. This distress has taken the form of pumping at pavement edges and extensive cracking. It is important to note that two types of asphalt treated bases may be used in Indiana. These are cold mix and hot mix. It is believed that the majority of the distress has been shown on the asphalt emulsion treated bases (cold mix), but this has not been determined with certainty.

The widespread use of asphalt emulsion treated mixture (AETM) in both the rigid and flexible pavement system was precipitated by the apparent economical and environmental advantages. Because of such potential advantages, considerable interest has developed in recent years for evaluating the properties of AETM and for developing mix design procedures and criteria for the asphalt emulsion treated mixtures. However, due to the complexity of the mix behavior under different loading and environmental conditions a more thorough understanding of the role of each of the AETM components is needed.

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*Numbers in parentheses refer to references listed in the bibliography.

The primary purpose of this study was to evaluate the significant factors that influence the properties of AETM as measured by the Marshall equipment with the following specific objectives:

1. To establish a method for preparing and testing asphalt emulsion treated mixtures (AETM) using the Marshall equipment.
2. To determine the influence of several factors (aggregate gradation, asphalt emulsion content, added moisture content, the use of additives, and curing time) on the properties and performance of asphalt emulsion treated mixture type especially used in Indiana.
3. To evaluate some additional design parameters (through the use of a load-deformation trace obtained from the autographic Marshall equipment) that could be considered in the mix design to better control the performance of the AETM.

CHAPTER II: LITERATURE REVIEW

Asphalt-Treated Mixtures

The stability of an asphalt mix is dependent upon the two major components, the asphalt and mineral matter. When subjected to stress, asphalt treated mixtures may exhibit flow properties of the asphalt or stable properties of the aggregate, depending upon the mix composition, temperature and loading conditions.

Various researchers have studied the factors affecting the properties and performance of asphalt-treated mixtures using different methods of test and evaluation (27, 28, 33, 45, 50). From these studies it can be concluded that several factors are important and affect the properties of the mix. These include: (1) aggregate type and gradation, (2) asphalt type and content, (3) compaction effort, (4) test temperature, (5) loading rate, and (6) curing time especially in case of using asphalt emulsions and liquid asphalts. In addition to these factors, the initial added moisture is a critical and important factor that affects the asphalt emulsion treated mixtures properties.

The Use of Asphalt Emulsion Mixtures

Treatment of base material with asphalt emulsions has several potential advantages over hot mix asphalt treatment. Most important is that either road mix or plant mix can be used. Heating of aggregate and asphalt may not be required, which represents an important point as far as pollution is concerned. However, the most critical shortcoming of asphalt emulsion treated material (AETM) is the relatively low strength at early ages and the slow development of strength which is limited by the rate of water loss in the structure (50). In addition, possibility of erosion and drop in mixture strength due to the presence of water in the system before curing is complete (46, 51) can be important.

Several researchers (14, 22, 46, 50, 51) have studied the curing behavior of AETM. In some of these studies (46, 50) the mixes were compared with hot mix materials. A resilient modulus, M_R, was used for evaluation. In these studies it was shown that the resilient modulus (M_R) which was used as an indicator of the stiffness of the AETM changes markedly as the curing developed. Terrel and Monismith (50) suggested that curing conditions prior to and after compaction may have a significant influence on the stiffness of the mix. Also, the type of curing (dry or moist) influences the rate of change of the moduli. Darter et al (14), studied the effect of asphalt residue content, curing time, compactive effort, and compactive moisture content on the properties of the mix. A constant initial added moisture was used. They utilized modified Marshall stability test, indirect tensile test, and resilient modulus test in the evaluation.

Schmidt et al (46) showed that at ambient temperature air cured AETM attained M_R values compatible, if not higher, to that of hot mixes made with the same asphalt. However, the presence of water had an adverse effect on its strength. Also, they demonstrated the reversible nature of the effect of water on AETM. A substantial drop in strength at early ages was observed, but the rate and magnitude of the decrease of strength, in the presence of moisture, decreased with the increase of curing time before moisture exposure. Also the M_R's of moisture-deteriorated mixes return to their original values upon drying.

Recognizing the adverse effect of water on the stiffness of asphalt treated mixes, in general, and AETM and liquid asphalt mixes in particular, several organizations have proposed test methods and design criteria for hot mixes (3, 6) and for AETM and liquid asphalt mixes (4, 5, 13).

In a study conducted by Dunning and Turner (17), an "evaluating system" for AETM was presented. AETM samples were evaluated (using a modified Hveem method and vacuum soaking apparatus) in three different conditions; uncured, cured, and soaked condition. Besides, a 2^2 statically designed experiment was recommended by them to permit the determination of the desired water and emulsion contents at compaction.

Moreover, considerable research has been done to promote the curing rate of emulsion mixtures and to provide better moisture resistance by means of using lime or portland cement as additives to the mix (23, 24, 29, 46, 51). Terrel and Wang (51) showed that using portland cement as a catalyst (1-3% by wt. of dry aggregate) would increase the rate of curing of AETM and accelerate the rate of development of M_R in the mix. Also, using up to 1% of portland cement helps overcome the effect of adverse curing conditions on the curing action of emulsion mixtures. Schmidt and Graf (45) demonstrated the advantages obtained by pretreating aggregate with lime. In recent research (46) using the same approach, the importance of using portland cement as an additive to AETM was demonstrated.

In another study Gietz and Lamb (24) indicated that higher Marshall stability values were obtained using lime or portland cement in an asphalt cement mix. Further, the importance of the use of portland cement in improving the AETM Marshall stability and its resistance to water damage was demonstrated in recent studies (23, 29). Dunn and Salem (16) have shown the significant effect of changing the order of addition of ingredients (mix components) during mixing on the specimens unconfined compressive strength.

In spite of these advantages, addition of cement has an effect on the fatigue performance of these mixes (46). Schmidt et al (46) indicated that asphalt treated material showed greater fatigue resistance than either AETM or cement modified AETM, and that AETM gave better fatigue performance than cement modified AETM. However, because of the exceptionally high M_R developed by cement modified AETM, it was concluded that the pavement thickness required for equal fatigue life showed that asphalt treated material and cement modified AETM (1.3% portland cement by wt. of dry aggregate) are equally effective.

Recognizing the advantages of using AETM and the beneficial effects of using additives suggests the need for the development of mix design method and critical property parameters for AETM.

Marshall Method of Mix Design

Several individuals have criticized this type of test, since it is mainly empirical and depends upon correlation between measured parameters in the laboratory and field performance. Nevertheless the Marshall test is considered to be one of the most widely used conventional methods for the design of asphalt concrete mixtures. The design method incorporates two main properties for evaluating the quality of an asphalt concrete mixture, stability (measure of strength and resistance to deformation under load) and flow (measure of plasticity and flexibility of the compacted mix). Density and voids analysis of the compacted mix are also performed.

Several projects have been conducted to define and study the properties measured in the Marshall test. Most of the research has been directed to study the influence of some of the variables on test results such as asphalt viscosity (21), compaction method (19) and specimen thickness (35). Some research has investigated the relationship between stability and flow and other fundamental parameters (26, 39, 41). Goetz and McLaughlin, (26, 39) indicated that the Marshall test is a type of confined test, in which the confinement is due to the curved shape of the testing head and that a good correlation existed between Marshall flow values and the angle of internal friction of the mix (an inverse linear relationship). McLeod (39) in his discussion susgested that the effective lateral support which develops in the Marshall test is variable and depends upon the coefficient of friction between the specimen and test head, maximum vertical load applied, angle of internal friction of the mix and shearing resistance of the material. Metcalf (41) analyzed the stress condition in a Marshall test after applying some assumptions. He showed that the bearing capacity of a paving mixture can be related to Marshall stability and flow by the following equation:

$$\text{Bearing Capacity (psi)} = \frac{\text{stability}}{\text{flow}} \times \frac{120\text{-flow}}{100}$$

Krokosky (34) studied the viscoelastic relationships that are inherent in the Marshall test. This was done using stress-relaxation tests on Marshall Specimens after modifying the apparatus to give a continuous record of the load and deformation.

Limiting criteria values are specified for the design of bituminous mixes using the Marshall method. In addition, the control over the voids characteristics, minimum limiting stability values and a maximum flow value are usually established (1). A minimum flow value is also recommended by The Asphalt Institute (3) and by AASHTO for surface courses (1) since mixes with abnormally low flow values tend to be brittle and less durable. However, it has been concluded by several researchers (9, 41, 52) that incorporating another parameter would provide a better standard for judging asphalt mix stability and performance. Metcalf (41) emphasized that the load carrying ability of an asphaltic mix is a function of both the flow value as well as stability and that neither Marshall stability nor flow values alone satisfactorily predict the performance of the mix.

In recent studies, Van de Loo (52) and Brien (9) concluded that Marshall stiffness (S_m, calculated as $\frac{\text{stability}}{\text{flow}}$) gave a better correlation with rut depth than did Marshall stability alone. Furthermore, Brien (9) suggested that as a tentative measure for mix performance, a minimum Marshall stiffness value should be used in the mix design. The Dutch mix specifications include minimum limiting values as "Marshall quotient Stability/Flow", beside the usual limiting values on Stability and Flow for the different mix types (52, 53). It has to be noticed that, in this case the Flow value is slightly different from the traditional standard definition and is measured from the load-deformation trace as the distance from the mid-point of the peak to the point of intersection of the linear portion with the horizontal axis which represent the deformation (refer to Figure 3, for a typical Marshall "load-deformation" trace).

Recently, several researchers have utilized the Marshall test procedure after some modifications for evaluating the AETM properties (14, 23, 29). In addition, some agencies (37) have modified the Marshall procedure to design AETM for use as base course, but no specific criteria are available for this procedure.

Permeability of Asphalt Treated Bases

One objective of using subbase material beneath rigid pavements is to provide an adequate drainage layer. However, the use of asphalt treated subbases produces a limitation relative to this point. Increasing the permeability of asphalt treated subbases may reduce its strength and stability. Because of the relatively low permeability that can be attained in asphalt treated material, the water may be trapped in the mixture producing a substantial drop in its stiffness as was discussed earlier. This can be attributed to the stripping action and loss of adhesion in the mix.

Several researchers have studied permeability characteristics of several types of bituminous mixes (18, 25, 30, 40, 47). In general, permeability of a mix is affected by the voids content of the total mix. Bitumen content and filler content affect the coefficient of permeability indirectly through their influence on the voids content. However, and till now, there has been no standard test for measuring permeability of asphalt treated material. Different types of permeameters are used by individual researchers and organizations (25).

Besides, in a recent study conducted in Indiana for evaluation of CRC pavements (20), asphalt emulsion treated subbase cores could not be recovered on any of the available field test locations. The instability of the subbase as indicated by the failure to obtain an intact core may be attributed to either partial curing of the AETM or water damage of the AETM due to presence of water. The later reason appears more likely as large amount of water was observed to drain from under the slab into the test pit on the shoulder together with the observed presence of water on the subbase AETM layer.

The main point that arises here is the need for using an effective stabilized mix which can provide good resistance to water erosion, but at the same time has enough permeability to allow the free escape of water. In addition, it is believed that prevention of water accumulation on or in the subbase is one method for improving pavement performance. This could be attained by applying adequate lateral drainage.

CHAPTER III: EQUIPMENT AND MATERIALS

Marshall Equipment

The Marshall equipment consisted mainly of a mechanical compaction hammer and an autographic stability apparatus. The mechanical compaction hammer, shown in Figure 1, was used for compacting the standard Marshall specimens with 50 blows per side.

The stability apparatus used in this investigation is essentially the same as the standard Marshall Equipment but it provides a continuous recording chart for the load (lbs.) versus deformation (0.01" units) throughout the testing range from which stability and flow values can be obtained.

Figures 2 and 3 show the general setup of the autographic Marshall equipment and an example of the recorder chart, respectively. A recorder that plugs into the press is used to provide the load-deformation chart. Three load ranges 0-2,500, 0-5,000, or 0-10,000 can be used in the recorder and all the three ranges appear on each chart. The signal from the load cell is translated into movement of the recording pen. The strain (chart drive) is controlled by an independent synchronous motor and gear train at 40 inches of chart per minute equaling 2 inches of press travel per minute. The chart abscissa is divided into divisions, each one equaling 0.01 inches of press head travel. A more detailed information and description is given in the manufacturer's catalog (44).

Materials

Mineral Aggregate:

1 - Source and Type:

One source of aggregate, consisting mainly of terrace sand and gravel obtained from the Western Indiana Aggregate Corporation gravel

FIGURE I , MECHANICAL MARSHALL COMPACTION HAMMER

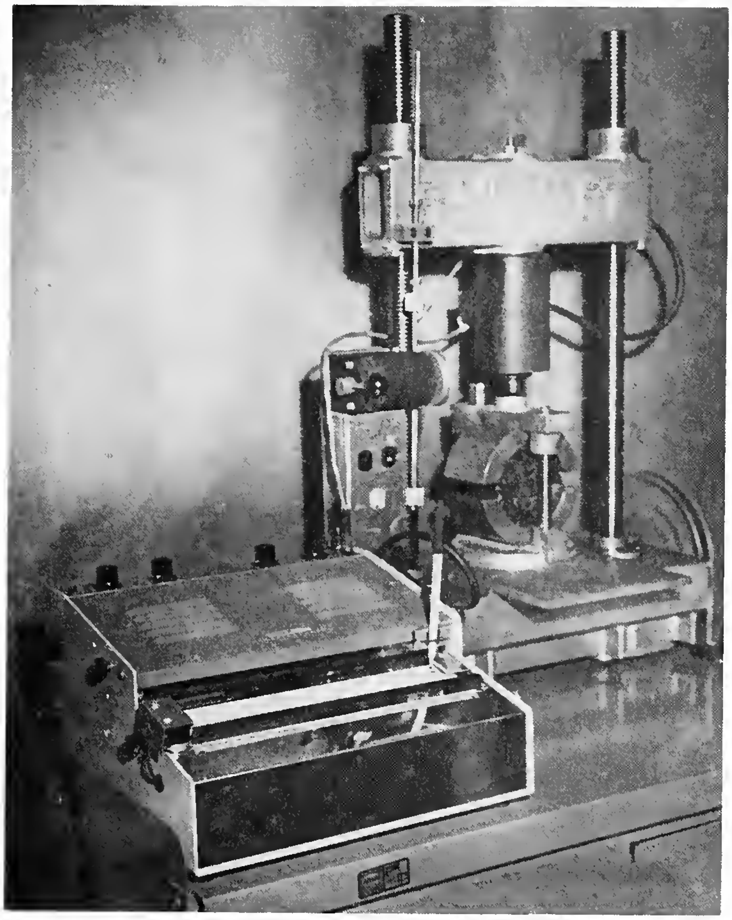


FIGURE 2 , AUTOGRAPHIC MARSHALL EQUIPMENT

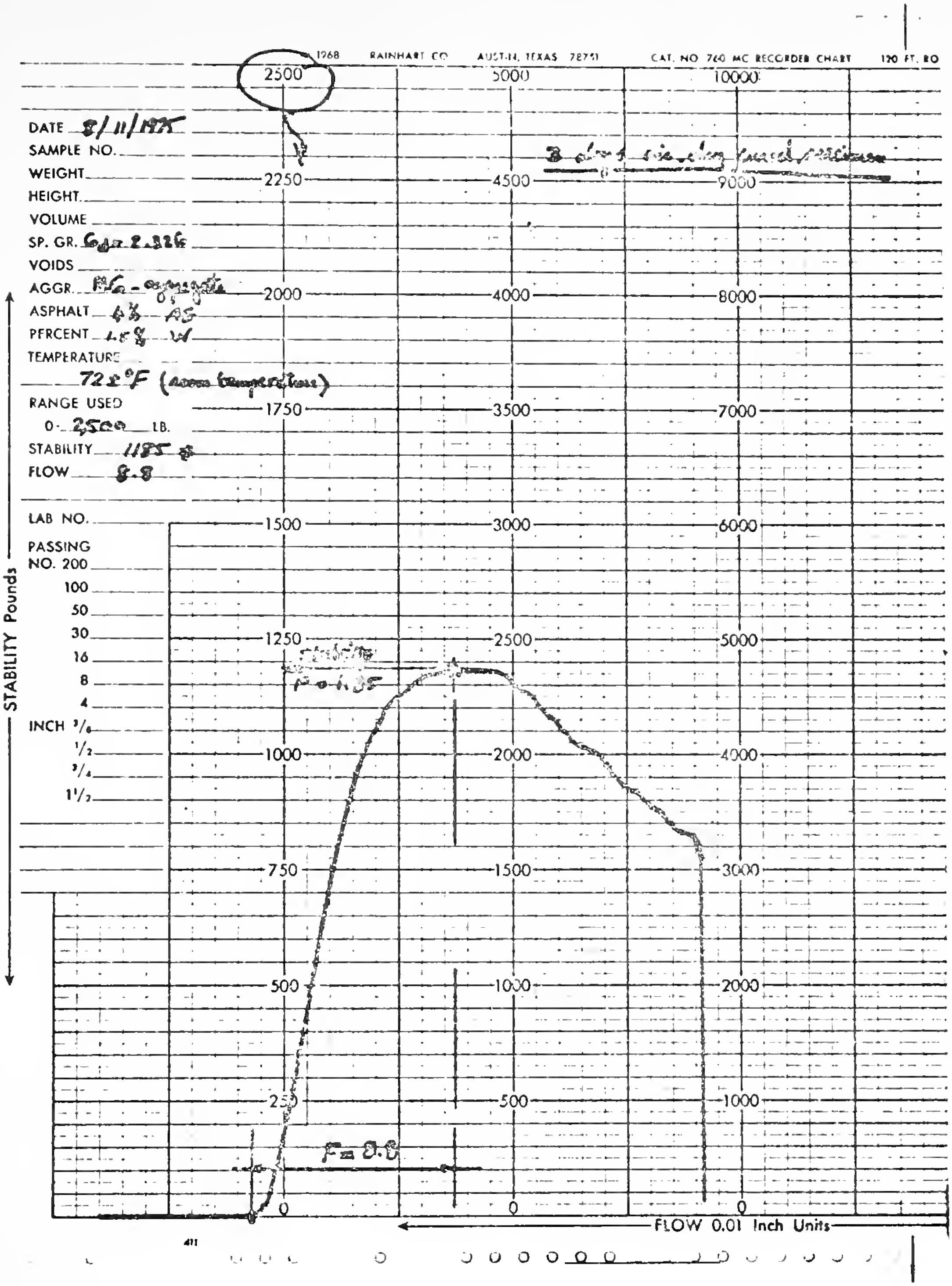


FIGURE 3 , TYPICAL RECORDER CHART FOR THE MARSHALL TEST

pit in West Lafayette, Indiana, was used in this investigation. The sand fractions were from an outwash deposit of the early Wabash River (12). This sand and gravel contained mainly weathered sedimentary rocks, limestone and dolomite being the most prevalent. Small amounts of granite and quartzite made up the remaining.

2 - Aggregate Preparation:

The aggregate was separated into the different sieve sizes. After conducting the necessary aggregate properties tests, the separated aggregates were recombined to the desired grading in 1200 gram batches. Three aggregate gradations that lie within ISHC gradation size #73B were utilized in this study (see Figure 4). The first gradation, MG, follows the mid specification of the ISHC #73B gradation band. The second gradation, FG, follows the upper limit of the gradation band. The third gradation, CG, was selected between the mid-point and the lower limit of the gradation band to provide better handling and control of the mix. Table 1, provides test properties of the aggregate used.

TABLE 1. AGGREGATE PROPERTIES

	Aggregate Gradation		
	FG	MG	CG
Apparent Specific Gravity	2.699	2.707	2.710
Bulk Specific Gravity, (SSD)	2.603	2.607	2.608
Absorption, %	1.13	1.20	1.24

Type of filler (-#200): non-plastic

Asphalt Emulsion:

AE-150 mixing grade emulsified asphalt was utilized in this study. The asphalt emulsion was formulated and provided by the K. E. McConnaughay Laboratory in Lafayette, Indiana. The physical properties of the asphalt emulsion are as follows:

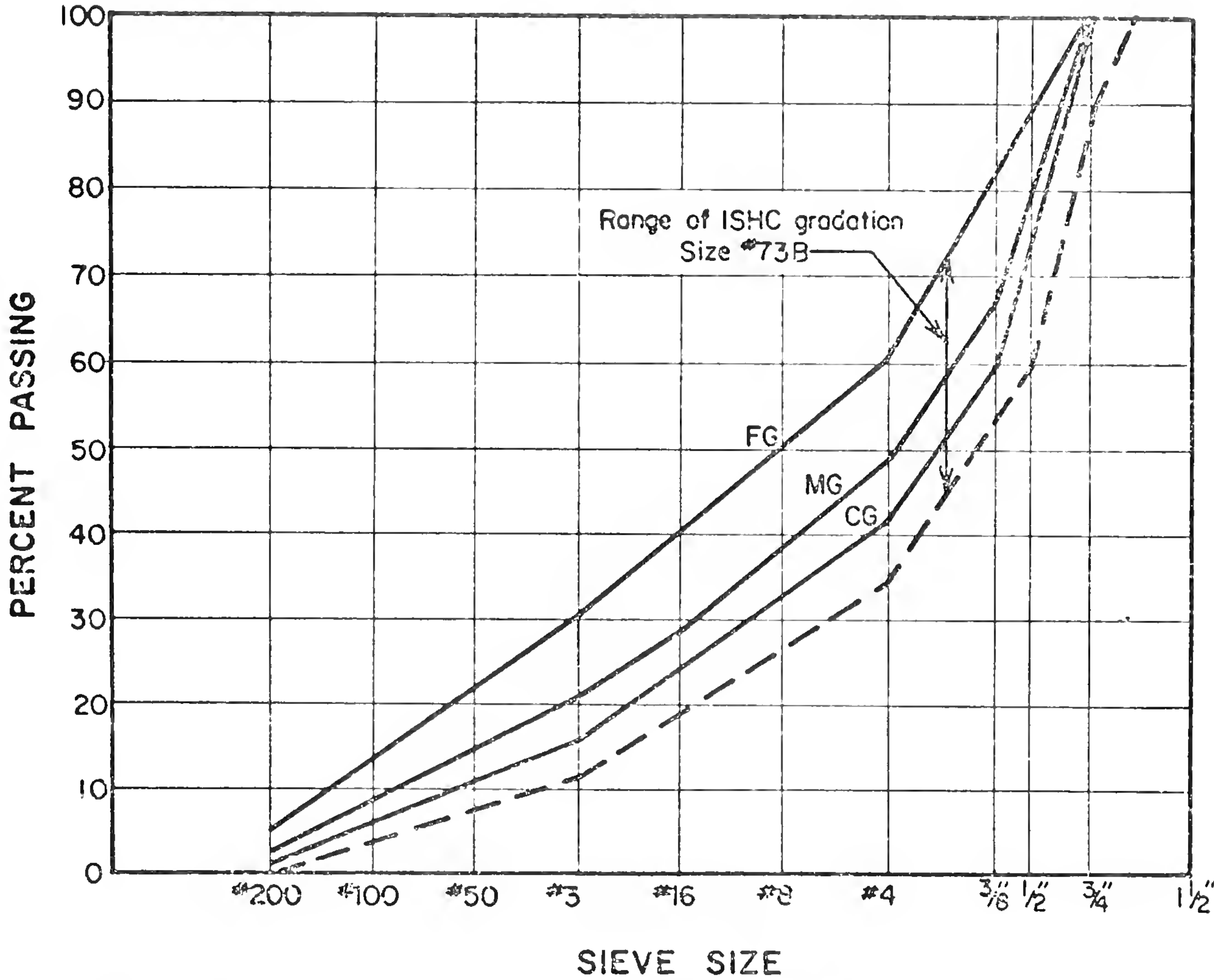


FIGURE 4 , AGGREGATE GRADATIONS

Residue by distillation, %	70.0
Penetration of residue after distillation, 77°F, 5 sec., 100 gm.	188.0
Specific gravity of residue after distillation, 77°F	0.986

CHAPTER IV: DESIGN OF THE EXPERIMENT

1. Introduction:

This study consisted mainly of two major sections. The first section dealt with establishing a method for preparing and testing asphalt emulsion treated mixtures (AETM) using the Marshall equipment. The AETM were evaluated with emphasis on the coating, workability of the mix, ease of handling of the mix and the standard Marshall specimen, curing rate and amount of moisture retained in the specimen before and after compaction. Based on these factors, a method for preparing the standard Marshall specimen was determined. In addition, a limited study was conducted to evaluate three different reported methods for water sensitivity tests in order to select an adequate method for AETM. The detailed analysis and study of the first section of this research is presented in Chapter V.

The second section of the study involved an evaluation of the influence of several factors on the performance of AETM, using the predetermined method of specimen preparation and testing procedure. The following discussion and experimental design deals mainly with the second section of this research.

2. Response (dependent) variables:

The response (dependent) variables that were used to evaluate the properties of AETM using the modified Marshall Method were as follows:

1 - Density; dry (γ_d) and wet (γ_w) density. The wet density refers to the density of the mix, including the moisture portion of it, at the time of testing. The dry density was determined by excluding the moisture portion in the specimen.

2 - Percent moisture retained in the specimen at time of testing, $\%WC_o$ (expressed as percent by weight of the dry aggregate). This was determined by drying the specimen, after testing, for 24 hours in a 300°F oven.

3 - Percent voids in the mix; this includes evaluating each of the following two parameters separately:

a) Percent air voids, $\%V_A$, which represent the percent of air voids available in the mix excluding the voids that are filled with moisture.

b) Percent total voids, $\%V_T$. This parameter represent the total amount of voids available in the mix and includes the air voids ($\%V_A$) together with the voids filled with moisture ($\%V_W$), that is, $\%V_T = \%V_A + \%V_W$.

The percent voids were determined on the basis of the apparent specific gravity of the aggregate and that no asphalt was absorbed into the aggregate.

4 - Marshall stability, P, measured at room temperature which was maintained at approximately 72°F and defined as the maximum load in pounds required to produce failure of the specimen.

5 - Marshall Flow, F; maximum deformation that occurs as the specimen reaches failure and expressed in units of 1/100 inch (0.25 mm).

6 - Marshall Stiffness, S_m; determined as the ratio of Marshall Stability and Flow ($S_m = P/F$).

7 - Marshall Index, I_m; which is represented by the slope of the linear portion of the load-deformation trace obtained from the autographic Marshall equipment.

The relationship among the Marshall test indices is shown in Figure 5. The two new parameters S_m, and I_m provide measures for the mix characteristics at the failure condition and throughout the loading process, respectively. It is believed that the use of these two parameters in conjunction with the traditional Marshall design parameters would provide a better control and evaluation of AETM. A more detailed discussion of these two parameters is presented in the following chapters.

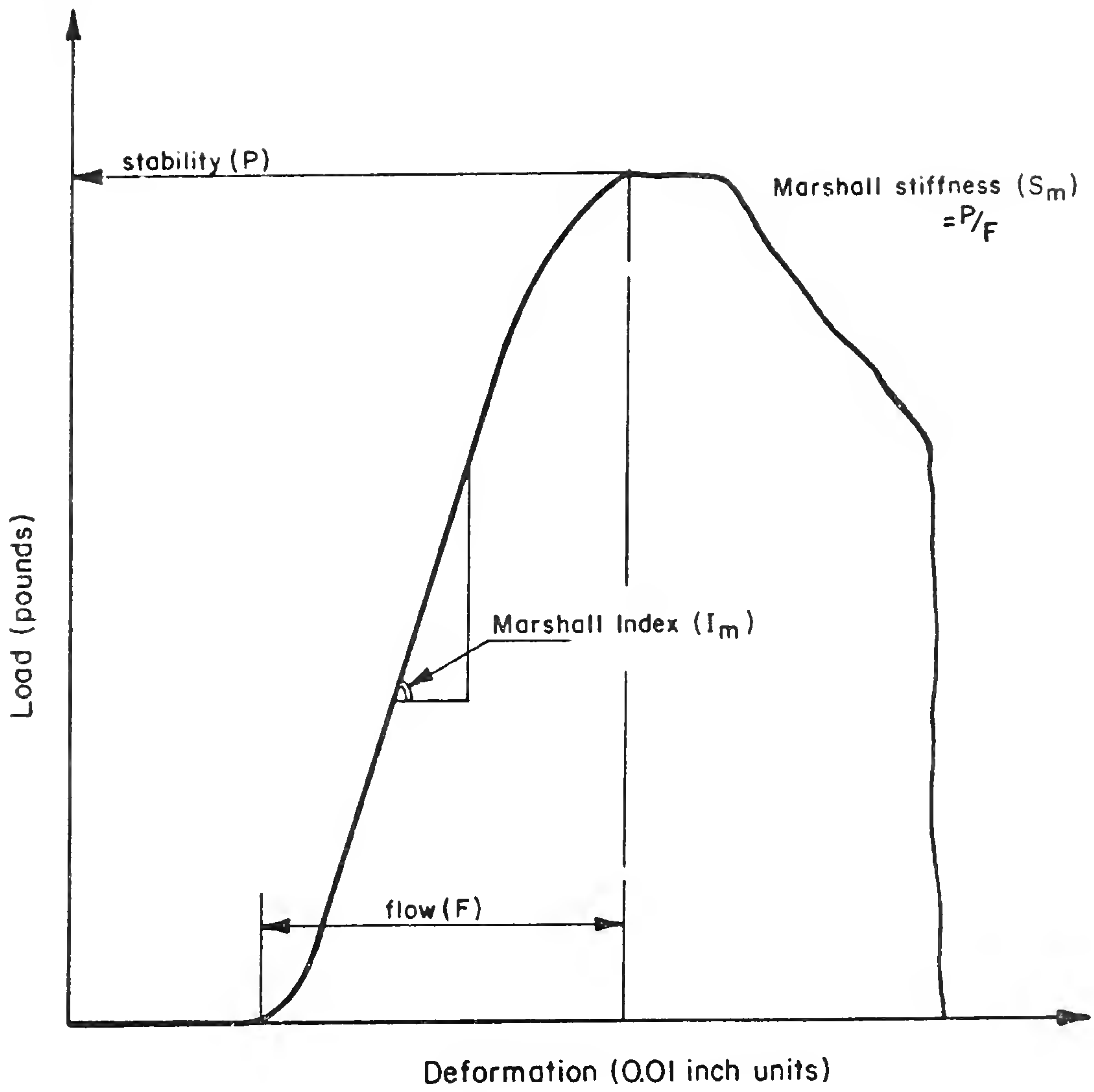


FIGURE 5, RELATIONSHIP AMONG MARSHALL STABILITY PARAMETERS; P, F, S_m AND I_m

3. Independent Variables (factors)

The factors that were evaluated in this study were as follows:

1 - Aggregate graduation, G; three levels of aggregate gradations were used. The three gradations were within the ISHC gradation #73B and given the symbols FG, MG, and CG, (for a more detailed description see p. 13 and Figure 4).

2 - Asphalt Emulsion residue content, %AE; three levels of %AE residue were used. The three levels were 2.5, 3.25, and 4.0% expressed as percent by weight of the dry aggregate.

3 - Initial added moisture, %W; four levels of %W were used in the first phase of the study (0, 1.5, 3.0, and 4.0%, expressed as percent by weight of the dry aggregate). After the first phase of the study, these four levels of %W were reduced to just two levels (1.5%, and 3%) and used throughout the evaluation part of the study.

4 - Curing time, C; five levels of curing of the compacted specimens were evaluated. The curing time levels were mainly; one, three, five, and seven days air-dry curing at room temperature which was maintained at approximately 72°F. The fifth level was used to simulate the "ultimate" curing condition (complete curing) of the AETM. This was attained by curing the AETM specimens for three days in a forced-draft oven at 120°F (51).

5 - Additives; two levels were used. In the first level no additives were used, while the second level represented the use of 1% Portland cement (by weight of dry aggregate) as an additive to the AETM.

It is of importance to mention here that the compactive effort was held constant throughout the study by using 50 blows of the mechanical compaction hammer on each side of the specimen.

4. Study design; phase I:

The effect of asphalt emulsion and added moisture contents on the AETM performance at early curing condition was evaluated using a 3 x 4 completely randomized design (Table 2) with three replicates per cell (mix combination). The two independent factors were:

TABLE 2, FACTORIAL DESIGN FOR STUDY OF THE EFFECT OF %AE AND %W ON AETM PROPERTIES

%W (added) \ %AE (residue)	2.5	3.25	4.00
0	X	X	X
1.5	X	X	X
3.0	⊗	⊗	⊗
4.0	X	X	X

Note:

Aggregate gradation: MG

Curing: one day air-dry curing

X: dry test

O: water sensitivity test

1 - Asphalt emulsion residue content, %AE; with 3 levels (2.5, 3.25, and 4.00%).

2 - Initial added moisture content, %W; with 4 levels (0, 1.5, 3.0, and 4.0%).

The other independent factors were held constant. The mid range aggregate gradation (MG) was used and no portland cement was incorporated. In addition, all tests were conducted on specimens cured for one day at room temperature.

This phase of the study was designed in such manner to provide a wider range of added moisture contents (%W), and consequently to allow for more understanding and evaluation of the effect of the percent added moisture and asphalt emulsion content and their interaction on the performance of AETM at early ages of curing (one day air-dry cured specimens). However, the effect of these two important factors (%AE and %W) together with their interaction with the other factors will be evaluated (after reducing the number of levels of %W to two levels) in the subsequent phases of the experiment as described below.

5. Study Design, Phase II:

Table 3 presents the factorial design that was used in Phase II of the evaluation section of the study. Three replications (test specimens) per cell were used to account for the variation within the mix combinations. The five independent factors; aggregate gradation, asphalt emulsion content, added moisture content, curing time, and additives are shown in the table. In addition, the mix combinations (cells) that were used in the water sensitivity tests are identified by a circle in Table 3. These mix combinations were selected to reduce the number of required specimens and at the same time to provide enough data for comparing the effect of the different factors on the AETM resistance to water damage.

Due to the destructive nature of the Marshall test and the large number of specimens required for the full factorial experiment, together with the large effort required to conduct the tests in a randomized manner, it was decided to design the experiment as indicated in Table 3. Restriction on randomization was imposed on the interaction between

TABLE 3, FACTORIAL DESIGN FOR STUDY OF FACTORS EFFECT ON AETM PROPERTIES (phase 2)

Additives	Curing time + condition	% W* \ Agg. Gradation / %AE (residual)*	F.G. 2.5	F.G. 3.25	F.G. 4.0	M.G. 2.5	M.G. 3.25	M.G. 4.0	C.G. 2.5	C.G. 3.25	C.G. 4.0
(NO P.C.)	1day	1.5 %	X	X	X	X	X	X	X	X	X
		3%	X	⊗	X	⊗	⊗	⊗	X	⊗	X
	3	1.5				X	X	X			
		3	X	⊗	X	⊗	⊗	⊗	X	⊗	X
	5	1.5				X	X	X			
		3				X	X	X			
	7	1.5	X	X	X	X	X	X	X	X	X
		3	X	X	X	X	X	X	X	X	X
	ult.+ cond.	1.5				X	X	X			
		3	X	⊗	X	⊗	⊗	⊗	X	⊗	X
(1% P.C.)*	1	1.5									
		3	X	⊗	X	⊗	⊗	⊗	X	⊗	X
	3	1.5									
		3	X	⊗	X	⊗	⊗	⊗	X	⊗	X
	5	1.5									
		3									
	7	1.5				X	X	X			
		3	X	X	X	X	X	X	X	X	X
	ult.+ cond.	1.5				X	X	X			
		3	X	X	X	X	X	X	X	X	X

Note:

X = dry test

O = water sensitivity test

* = percent by weight of the dry aggregate

+ = 3 days curing at 120°f

additives and curing time. All mix combinations have to be prepared and tested in a randomized manner within a certain level of additive and curing time before proceeding to the next block (additive X curing). In addition, it was decided to partially evaluate all the independent factors in such way to reduce the unnecessary large number of cells (mix combinations). This was achieved as follows:

1 - All mix combinations (cells) at the MG level of aggregate gradation without additives have to be performed to provide adequate information about the effect of asphalt emulsion and added moisture contents together with their interaction with curing time on the performance of AETM. These combinations will be referred to as Design No. 1.

2 - All mix combinations at two levels of the curing time and without portland cement (one and seven days of curing were chosen for this purpose) would be included in the analysis to evaluate the effect of aggregate gradation together with %AE and %W and their interactions. These combinations will be referred to as Design No. 2.

3 - All mix combinations at just one level of added moisture content (3%) would provide more information about the effect of aggregate gradation, G, asphalt emulsion content, %AE, and their interaction with curing time and additives, (Design No. 3).

4 - Curing time of 5 days was introduced for just the MG aggregate in Design No. 1.

5 - Water sensitivity tests were conducted on pre-selected mix combinations to provide enough information for a comparison purpose, ad indicated in Table 3.

As a result of the preceding discussion the final partial analysis was conducted in the following manner: (3 replications per cell were used in the entire experiment together with two more replications for the water sensitivity tests whenever it was conducted).

a) Design No. 1: A 5x2x3 factorial design, at the MG level of the aggregate gradation and 0% portland cement additive. The independent factors were:

1. Curing: 5 levels (1, 3, 5, 7 days & ult. condition)
2. %W : 2 levels (1.5%, and 3%)
3. %AE : 3 levels (2.5%, 3.25%, and 4.0%)

b) Design No. 2: A 2x3x3x2 factorial design, no additives were used. The independent factors were:
   1. Curing: 2 levels (1 and 7 days)
   2. Aggregate gradation: 3 levels (FG, MG, and CG)
   3. %AE : 3 levels (2.5, 3.25, and 4.0%)
   4. %W : 2 levels (1.5, and 3.0%)

c) Design No. 3: A 2x4x3x3 factorial design, using one level of %W (3%). The independent factors were as follows:
   1. Additives: 2 levels (0% P.C. & 1% P.C.)
   2. Curing : 4 levels (1, 3, 7 days and Ult. condition)
   3. Gradation: 3 levels (FG, MG, and CG)
   4. %AE : 3 levels (2.5, 3.25, and 4.0%)

CHAPTER V: EXPERIMENTAL PROCEDURES

The main purpose of this chapter is to provide the reader with a step by step outline of the procedure that was used to develop the AETM specimen preparation and testing procedures. Following that, an evaluation of the water sensitivity tests is presented. A brief outline of the testing procedures (for dry and soaked specimens) is presented at the end of this chapter.

Development of the Preparation and Testing Procedures for AETM "Marshall Specimens"

1. Material Handling and Specimen Preparation

The first objective of this study was to determine the feasibility of using the Marshall Method, after some modifications, for testing and design of asphalt emulsion treated mixtures (AETM). In this type of bituminous mixture and due to the fact that more factors in the AETM component system affect its performance during mixing and specimen preparation, more effort needs to be expended in controlling and handling the mix than the traditional hot mix types. The main factors that have been evaluated to provide an adequate method for preparing and testing AETM specimens are: coating of aggregate, workability of the mix and the trend of the moisture retained in specimens before and after compaction (curing rate).

This chapter is divided into parts that deal with the different steps of preparing the AETM specimens. Figure 6 provides a schematic diagram that presents the different steps that were considered in selecting a preparation and mixing method. Parallel to this process the amount of moisture retained in the mix at various curing periods was studied for two cases; precompaction curing case (loose state), and after compaction curing (compacted specimen). This former study was

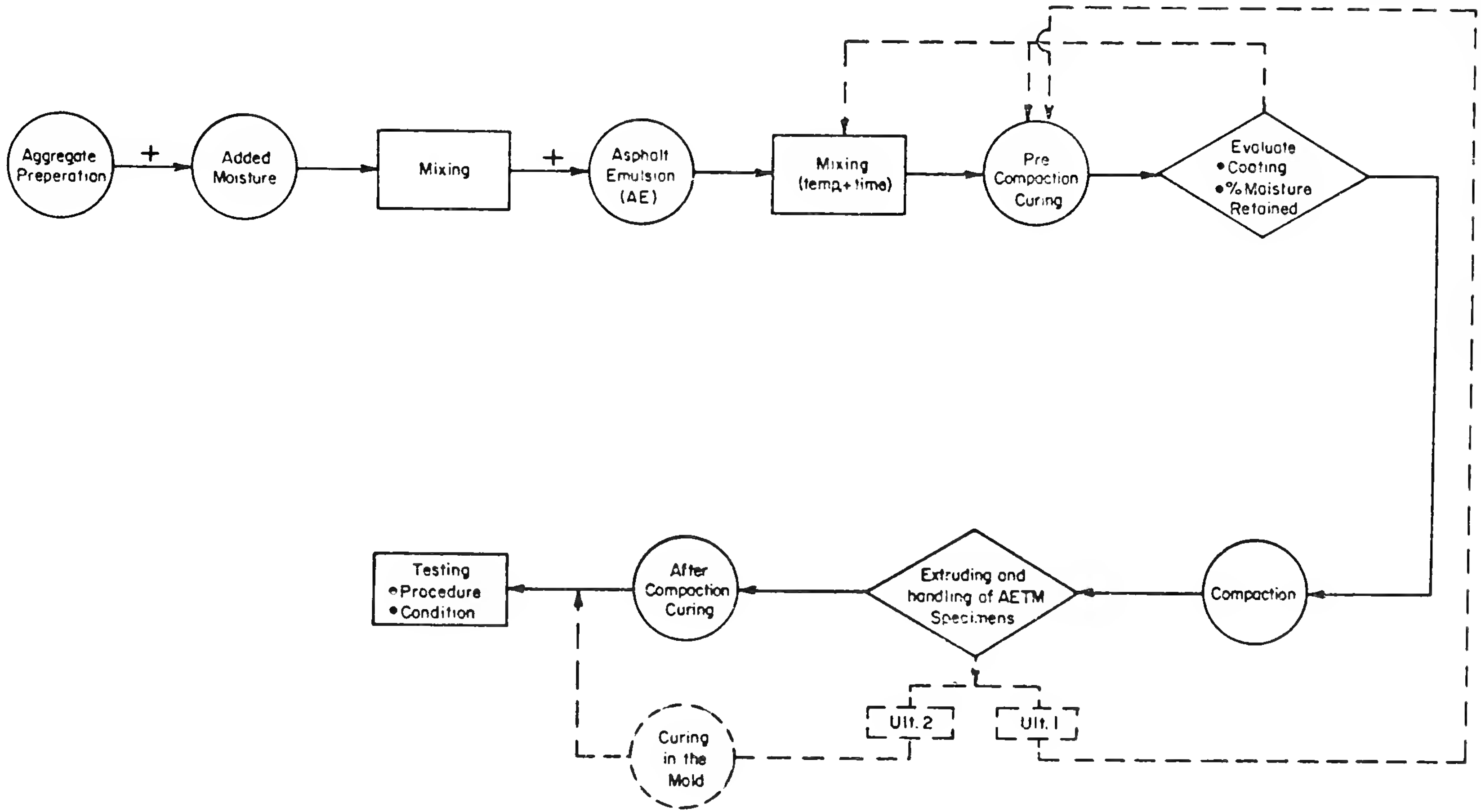


FIGURE 6, FLOW DIAGRAM FOR SELECTING AETM PREPARATION AND TESTING PROCEDURE

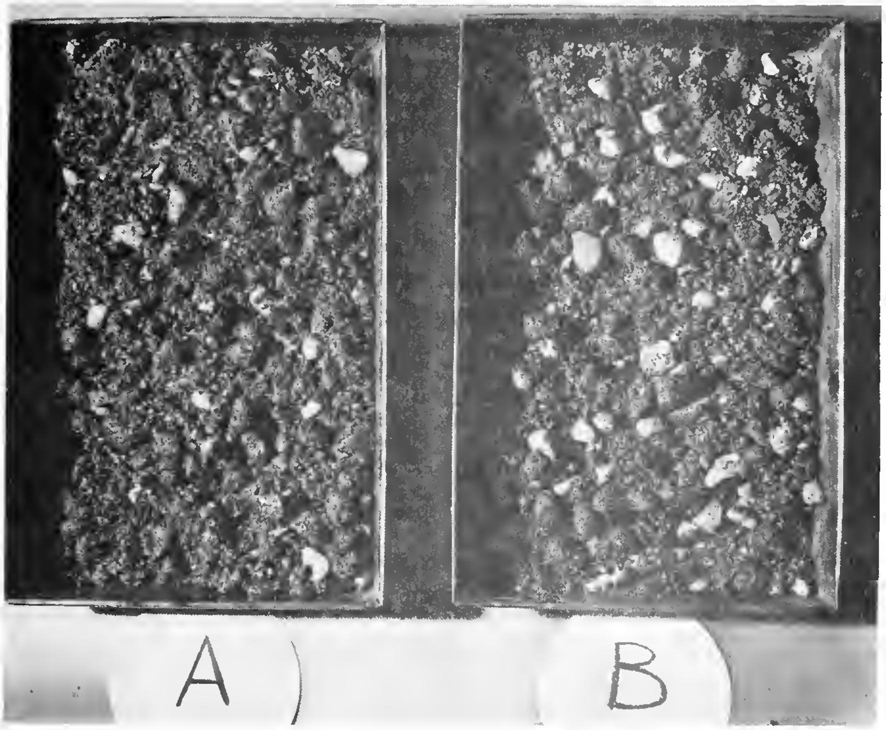
conducted for samples containing MG aggregate, 4% add moisture, and 4% AE residue. In addition, a limited study was conducted to determine the amount of moisture retained at time of compaction using different combinations of %W and %AE residue.

The dry aggregate was blended into 1200 gm. batches by combining the different aggregate sizes to the desired gradation. The aggregate was used cold (at room temperature) in the preparation of the AETM. The initial moisture content was added to the aggregate and mixed thoroughly. The mix was left for about 10-15 minutes at room temperature before adding the asphalt emulsion.

In the second step of the procedure, the asphalt emulsion was added cold to the wet aggregate and mixed thoroughly with a mechanical mixer for about 2 minutes with a 30 second hand mix with a spoon within the mixing period. This hand mix period was used to overcome the segregation of the fine and coarse aggregate during the mixing process. The suitablity of the mix and degree of coating was then evaluated.

Generally, the energy provided in the field during the preparation of the mix produces a better coating than that obtained in the laboratory using a completely cold procedure. Taking this into account and to provide a reasonable coating of the aggregate and consequently ease of handling of the mix and specimens, curing of the mixture for one hour at a forced-draft oven at 140°F was provided before remixing and compaction. In this case, the mix temperature reached about 110-120°F at the oven. It is generally accepted that this temperature level is reasonable for cold and intermediate asphalt emulsion treated mixtures. This stage in the mix preparation was selected after comparing and evaluating different conditions for handling the mix before compaction.

Figure 7 presents an example of two samples A and B; the two samples consisted of MG aggregate, 4% AE, and 3% added moisture. Mix A was cured for one hour at 140°F and remixed while mix B was prepared by completely cold mixing with a 15 minute curing at room temperature. The difference in the degree of coating and percentage of coated aggregate in these two samples can be seen in the figure.



(A) Cold mix + 1 hour curing at 140°F + remix

(B) Cold mix + 15 min. curing at room temperature

FIGURE 7, DEGREE OF COATING FOR AETM SAMPLES AT TWO CONDITIONS

In addition, precuring the mix before compaction provides a better condition when using Marshall compaction hammer which is mainly an impact compaction. It was noticed that using Marshall compaction for the uncured cold mix was not adequate due to the fact that the impact action forced part of the initial moisture available in the mix to escape with some fines. This was coupled with problems that arose from the handling of specimens after compaction especially while extruding them.

Compaction of the AETM was conducted at room temperature following remixing of the precured samples. 50 blows of the Marshall compaction hammer on each side of the specimen was used throughout the entire study. The problems involved in extruding the specimens from the molds were evaluated at different curing times after compaction in conjunction with the pre-compaction curing conditions. For the selected pre-compaction curing conditions (1 hour at 140°F, then remix before compaction), it was found that extruding the specimens after about a half an hour following the compaction is adequate, however with some of the mixes care must be taken in handling the specimen (e.g. CG aggregate mixes, samples with low %AE and/or high %W).

2. Study of the Relative Moisture Retained in the Sample

Together with developing the preparation and mixing procedure it was necessary to study the effect of curing time on the relative moisture retained in the samples before and after compaction, that is at the loose and compacted or dense condition. Two conditions for the before compaction curing (mix is in a loose condition) were studied. The first is based on a complete cure after the mixing process at room temperature which was approximately 72°F. The second case was for samples cured for one hour at 140°F, then remixed and left to cure at room temperature throughout the curing period. For the after compaction curing trends (mix is in a dense condition), three cases were evaluated and outlined as follows:

Precompaction Curing	After Compaction Curing
15 min. at room temperature	I. in the mold, at room temperature.
	II. out of the mold, at room temperature
1 hr. at 140°F + Remix	III. out of the mold, at room temperature

All samples were prepared using MG aggregate, 4% AE residue and 4% initial added moisture. Figures 8 and 9, show the effect of curing time on the percent moisture retained in the sample before compaction (loose condition) and after compaction, respectively.

It is apparent that the rate of moisture loss is faster for the pre-compaction as opposed to the after compaction samples. Most of the moisture loss in the pre-compaction cases occurred at an early time, i.e. during the first two days, after which the loss is not significant. However, for the samples cured for one hour at 140°F, the percent moisture retained dropped appreciabily in the first 12 hours and then followed the same trend as the samples that were completely cured at room temperature on the 2nd day (see Figure 8).

The loss in the percent moisture retained for the after compaction curing conditions was less than that obtained for the curing before compaction which is mainly due to the loose condition of the mix in the before compaction cases as opposed to the compacted state of the mix in the second case in which it will be more difficult for the moisture to leave the specimen.

Curing the sample out of the mold is beneficial as far as increasing the rate of moisture loss since it provides more surface area for the moisture to leave the specimen if compared with curing in the mold (see Figure 9). Also, the percent of moisture retained in the compacted specimens that were subjected to 1 hour at 140°F and remixed before compaction (curve III, Figure 9) was appreciably less than the other two conditions (curves I and II). However, this difference decreases with time and starts following the same trend after about 2 days.

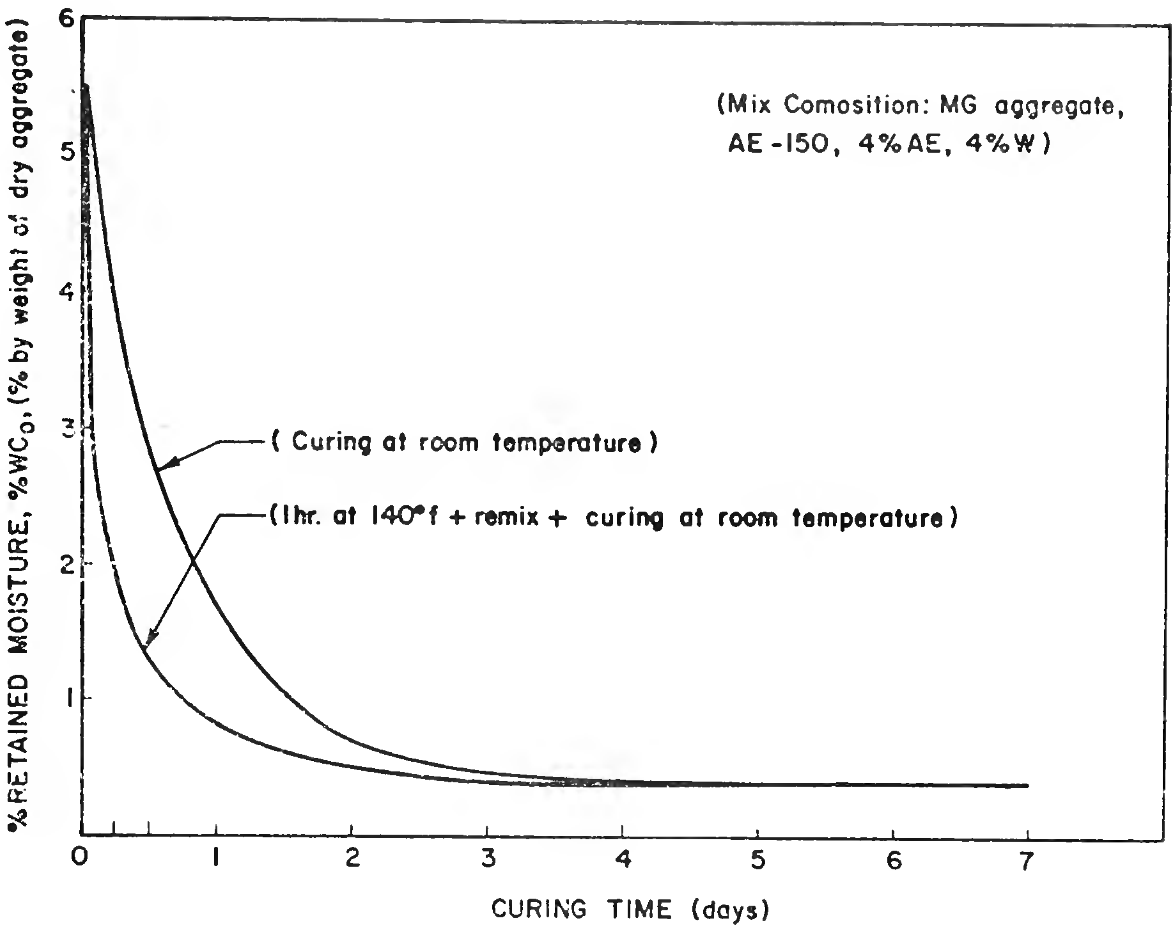


FIGURE 8, EFFECT OF CURING CONDITION ON THE AMOUNT OF MOISTURE RETAINED IN THE LOOSE MIXES (before compaction condition)

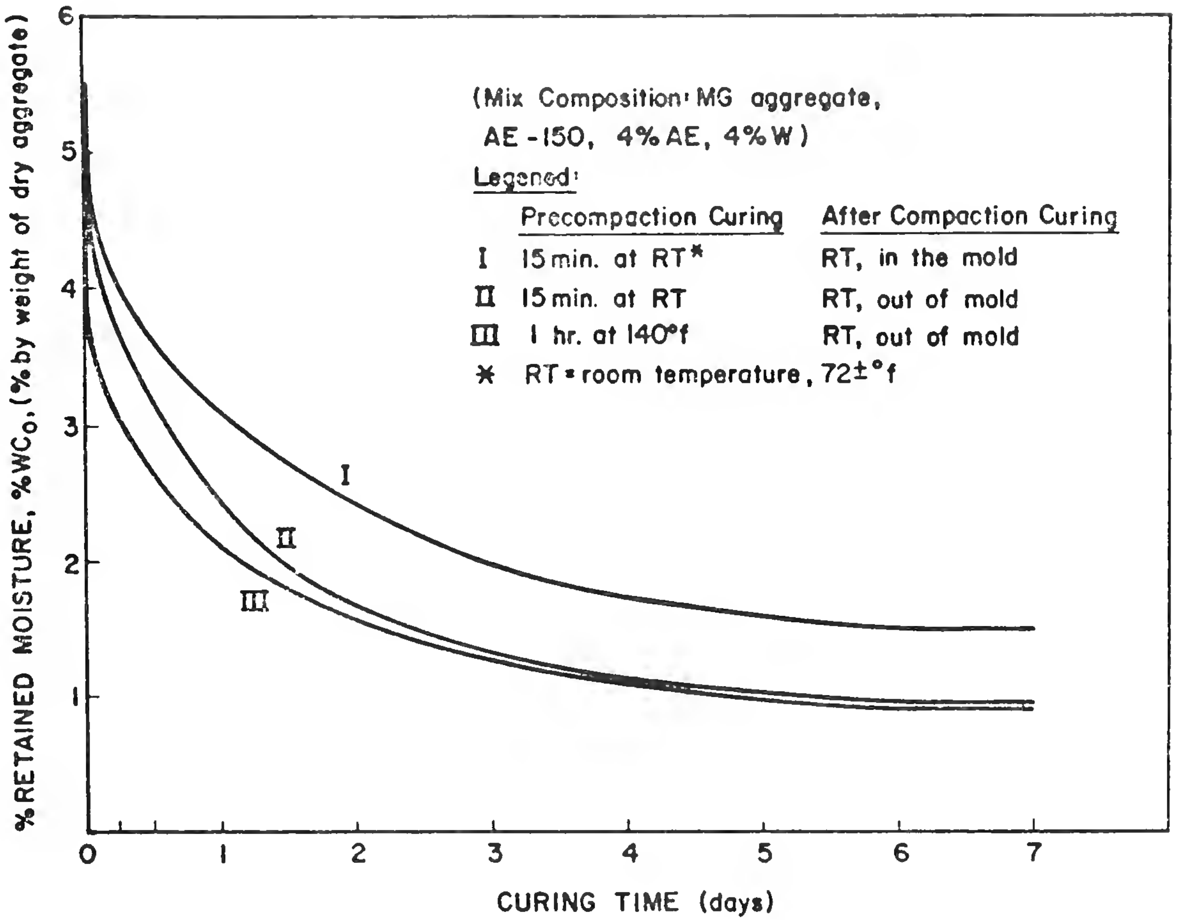


FIGURE 9, EFFECT OF CURING CONDITION ON THE AMOUNT OF MOISTURE RETAINED IN THE COMPACTED SPECIMEN (after compaction curing)

3. <u>Percent of Moisture Retained at Time of Compaction</u>

In conjunction with the preceding work, a limited number of samples were studied using different %AE residue (2.5-4%) and percent of added moisture (1.5, 3, and 4%) with the same aggregate gradation, MG. The specimens were cured for 1 hour at 140°F and remixed before compaction. The results showed that the relative percent retained moisture at time of compaction, expressed as percent by weight of the initial available moisture (initial added moisture + water portion of AE) ranges between 65% and 78%. Also, for a specific amount of added moisture, the relative percent retained moisture at time of compaction was about the same for samples with different %AE.

4. <u>Standard Marshall Specimen Preparation Method</u>

Based on the evaluation study, the following is a summary of the procedure that was used for preparing AETM specimens:

1. The aggregate was prepared in 1200 gm batches, based on the aggregate gradation required.
2. The required amount of initial moisture (distilled water) was added to the cold aggregate and mixed thoroughly.
3. The aggregate-water mixture was left for 10-15 minutes before adding the asphalt emulsion.
4. The required amount of asphalt emulsion that is needed to provide a certain asphalt emulsion residue content in the mix was added cold to the wet aggregate and mixed using a mechanical mixer for about 2 minutes with a 30 sec. hand mix with a spoon within the mixing period.
5. The mix was cured for one hour in a forced-draft oven at 140°F and then remixed for 30 sec.
6. Using the Marshall compaction mechanical hammer the mix was compacted using 50 blows on each side of the specimen.
7. The compacted specimens were left in the mold for about 1/2 hour before extruding them.

8. The samples (4" diameter x 2.5" height) were then left to cure at room temperature (≈72°F) for the required curing time before testing. Whenever the design called for the "ultimate" curing condition, the AETM specimens were cured for 3 days in a forced-draft oven at 120°F. The specimens were then permitted to adjust to the room temperature (72°F) before testing. Generally, 4 hours were enough for the samples to adjust to the room temperature.

Evaluation of Water Sensitivity Tests

A comparative study was conducted using three recommended water sensitivity tests (4, 5, 13). The mix combinations were a MG aggregate, 3.25% AE residue, and 3% initial added moisture. The study was conducted for three different curing conditions; one day cured specimens at room temperature, 3 days cured specimens, and completely cured specimens (3 days at 120°F oven). A brief description of the three water sensitivity tests that were evaluated is given below.

I. Specimens were soaked in a water bath at 72°F for four days before testing to determine the percent water absorption (% moisture picked-up) and percent retained stability. It has to be mentioned here that the Asphalt Institute calls for the use of 77°F water bath (4), but it was decided to adjust the temperature to 72°F to be able to test the soaked specimens at room temperature.

II. The second method was recommended in a recent laboratory report from the Asphalt Institute (5). In this method the specimens were subjected to one hour of vacuum at 30 mm Hg. After the one hour period, 72°F water was drawn into the vacuum chamber submerging the specimens and vacuum saturating them (Figure 10). The vacuum is released and the specimens were then transferred to a 72°F water bath where they remained for 24 hours. Prior to testing for Marshall Indices the saturated surface dry weight of the specimens was determined. The percent water absorption was then obtained.

FIGURE 10, VACUUM SATURATION APPARATUS

III. This method utilizes the vacuum soaking procedure (4, 13). The specimens are placed in molds into a vacuum apparatus and allowed to soak in water. The desicator then is evacuated to 100 mm of Hg for one hour. The vacuum is then released and the specimens allowed to soak in water for one more hour before testing it.

For each curing condition 12 specimens were fabricated and grouped at random into 4 groups, one to be tested dry as a control set and the other three groups tested using the three different water sensitivity tests. Table 4, presents the general properties for the mix combination and for the test samples at each curing condition.

The results of the study are shown in Figure 11 and indicate that the methods 2, and 3 are comparable. It can be seen from Figure 11 that method No. 2 enabled the specimens to absorb more moisture than method 3. However, this difference is not significant. This difference could be attributed to the longer time that the specimen has to be soaked in the water before testing. Comparing the results of method No. 1 with the other 2 methods reveals that method No. 1 is more severe on the AETM specimen. The water damage in this case is mostly due to the surface deterioration of the specimen especially for specimens cured for brief periods of time (note in Figure 11, one day cured specimens failed before conducting stability tests). It should be kept in mind that this type of AETM has a low resistance to water damage during the early stages of curing due to lack of bonding between the mix components and the slow development of strength. Thus, it is clear that this method is not appropriate for this type of mix, especially if it is used for early cured samples.

From the above discussion it was decided that method No. 2 was best suited to evaluate the water sensitivity of the particular AETM used in this study.

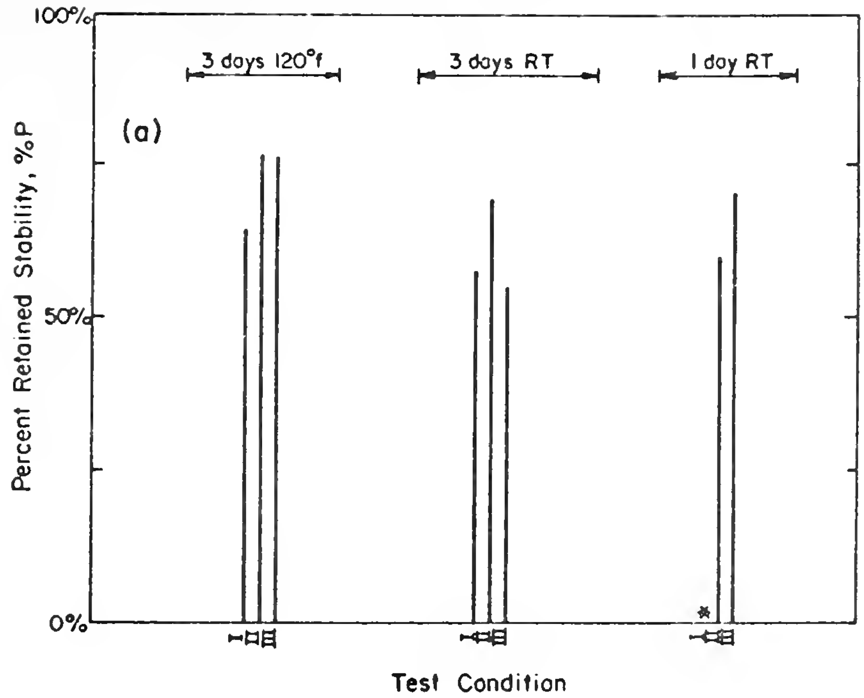
Effect of Soaking Time

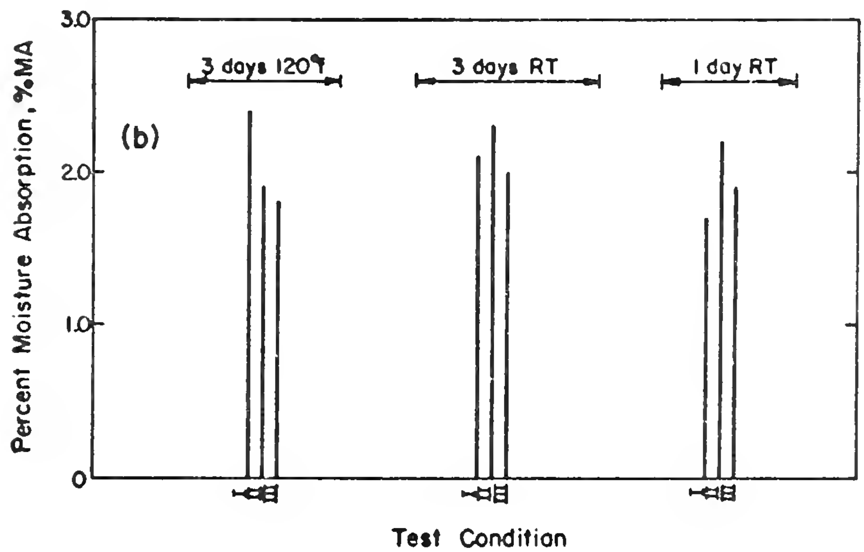
The effect of extending the soaking time for method 2 is presented in Figure 12. A large percentage of the amount of total moisture absorped occurred in the first day of soaking after which the amount of increase is very small which indicates that soaking for one day is

TABLE 4. GENERAL DATA FOR THE TEST SAMPLES BEFORE THE WATER SENSITIVITY TESTS

- MG aggregate
- 3.25% AE residue
- 3.0% added moisture

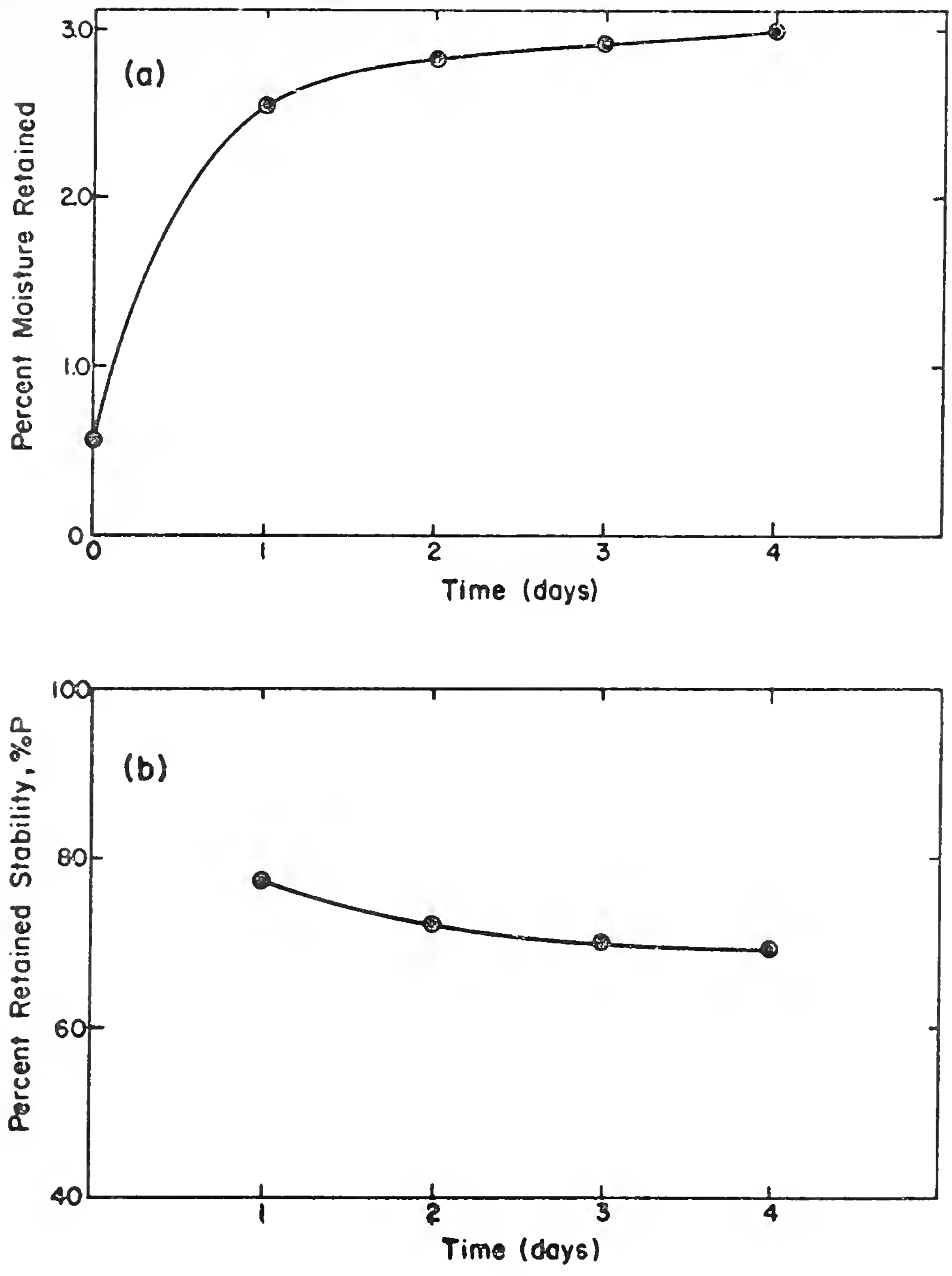
Curing Condition	1 Day Curing at Room Temperature	3 Days at Room Temperature	Ultimate Condition
G_d	2.313	2.310	2.318
G_w	2.354	2.336	2.330
$\%WC_o$	1.54	1.18	0.52
$\%V_A$	6.3	7.3	8.4
$\%V_w$	3.5	2.7	1.3
VMA	17.2	17.4	17.0





Note:
Mix composition: MG aggregate; 3.25 %AE, and 3%W
I = 4 days at 72°f water path (4)
II = asphalt Institute (5)
III = vacuum soaking (13)
* = samples failed before conducting the stability test

FIGURE 11, COMPARISON OF DIFFERENT WATER SENSITIVITY TEST RESULTS



Note:

1- Mix composition: MG aggregate, 3.25% AE, and 3.0% W

2- Samples cured for 3 days at 120°f (ultimate condition) before the water sensitivity test

FIGURE 12, EFFECT OF SOAKING TIME ON: (a) PERCENT MOISTURE RETAINED, AND (b) PERCENT RETAINED STABILITY

adequate for evaluating water sensitivity. However, increasing the soaking period results only in surface deterioration of the samples cured for short periods of time as was mentioned before. Besides, the reduction in stability also levels out after 2 days of soaking (as seen in Figure 12). It has to be noted that these last tests that dealt with the effect of soaking period were conducted using fully cured specimens.

Summary of Testing Procedures

The cured AETM specimens were tested at room temperature using the Marshall equipment to determine the Marshall Stability, Flow, Stiffness, and Index. Prior to testing, density-air voids analyses were performed. Whenever the design called for conducting water sensitivity analysis (see Table 3) the method reported by the Asphalt Institute laboratory (5) was used.

CHAPTER VI: EFFECT OF ASPHALT EMULSION* AND ADDED MOISTURE CONTENTS ON AETM PROPERTIES

Introduction

This portion of the study represents the first phase of the evaluation of the AETM properties. The primary objective was to evaluate the effect of asphalt emulsion and added moisture contents on the properties of AETM at <u>early curing conditions</u> and over a relatively wide range of added moisture contents. One aggregate gradation (MG) was used in this phase of the study. All test results are for one day air-dry cured specimens.

Table 2 in the Chapter on Design of Experiment presents the factorial design of this part of the study. Three levels of asphalt emulsion content (%AE) and four levels of added moisture content were used. This design resulted in twelve different mix combinations (cells). Three replicate specimens were tested in each mix combination. In addition, two specimens were tested for the water sensitivity analysis in each one of the three mix combinations that incorporated the use of 3% added moisture.

Analysis of Results

The analysis of variance was based upon a two-way completely randomized design using the model:

$$Y_{ijk} = \mu + A_i + W_j + AW_{ij} + \varepsilon_{(ij)K}$$

---

*Whenever the expression "Asphalt emulsion content" is mentioned it refers to the asphalt emulsion <u>residue</u> content in the AETM.

where

Y_{ijK} = Measured or response variable

μ = Overall true mean effect

A_i = True effect of the asphalt emulsion content, %AE

W_j = True effect of the added moisture content, %W

AW_{ij} = interaction effect between A_i and W_j

$\varepsilon_{(ij)K}$ = true error, NID (o,σ^2)

The main effects A and W are fixed. The subscripts assume the values:

i = 1, 2, 3

j = 1, 2, 3, 4

K = 1, 2, 3

In this analysis (and that to follow in the subsequent parts of the study) homogeneity of variance was checked prior to making the analysis of variance. Validity of the assumption of homogeneity of variance was tested by Foster-Burr test [q-test, (10)]. The homogeneity was accepted if the q-test values were less than the q-critical values for $\alpha = 0.001$, and consequently the original data were used in the analysis of variance (2), However, if the homogeneity of variance for any of the dependent variables was not accepted an appropriate transformation was applied to the original data before making the analysis of variance.

Generally, transformations which improve the heterogeneity of variances also improve the lack of normality, if it exists, (2). In addition, analysis of variance is a fairly robust statistical method, especially if dealing with fixed model with equal sample sizes (as in the case of this evaluation study), and is relatively insensitive to violations of the assumptions of normality and homogeneity of variances (8).

The q-test for homogeneity of variance (for the different dependent variables that were used) gave values on the range of 0.128 to 0.333 as compared with the critical values of 0.276 for $\alpha = 0.01$ and 0.358 for $\alpha = 0.001$. Therefore, analysis of variance was performed on the

original data.

Table 5, presents a summary of the ANOVA for AETM response variables. In addition, a typical analysis of variance table is shown in table B1 in the appendices. The response variables $\%V_A$ and $\%V_T$ were not included in the ANOVA because they were determined as an average of the three replicates for each mix combination (which is the usual practice). This will not provide an adequate analysis and the ANOVA would have to be based on some assumptions which could be unreasonable in this case. It is believed that treating the data as such and explaining its physical trends will provide a better understanding.

The following sections of this chapter will deal with the evaluation of each one of the response (measured) variables, this will include discussion and interpretation of the ANOVA results together with studying the physical trends of the response parameters.

Percent of moisture retained in the sample, $\%WC_O$

Both the asphalt emulsion and added moisture contents significantly affect the amount of moisture retained in the sample at time of testing. Also, the added moisture content affected the percent of moisture retained more than the asphalt emulsion content. However, the interaction between the asphalt emulsion and added moisture contents was not significant. For a specific added moisture content the percent of moisture retained is directly related to the percent asphalt emulsion. At the same time, at a given %AE, the amount of moisture retained increases with increasing the added moisture content. As it can be seen in figure 13, the effect of added moisture content is more pronounced than that of varying the asphalt emulsion content.

Figure 14 presents the results of percent moisture retained in the sample at time of testing expressed as a percentage of the original available moisture (added moisture + moisture portion of AE). At a specific added moisture content, the percentage of moisture was about the same for samples with different asphalt emulsion contents and it decreased with increasing the initial added moisture.

It is apparent from this discussion that the added moisture content has a greater influence on the percent retained moisture than the asphalt

TABLE 5, SUMMARY OF ANOVA RESULTS FOR AETM PROPERTIES (one day cured specimens ; MG aggregate)–(phase I)

Source of Variation \ Response Variables		γ_d	γ_w	$\%WC_o$	P	F	S_m	I_m
A	%AE	S	S	S	N.S.	S	S	S
W	%W	S	S	S	S	S	S	S
AW		S	S	N.S.	S^+	S	S	S

Note:

1- S = Significant at $\alpha = 0.05$
2- S^+ = Significant at $\alpha = 0.10$
3- N.S. = Not significant at $\alpha = 0.10$

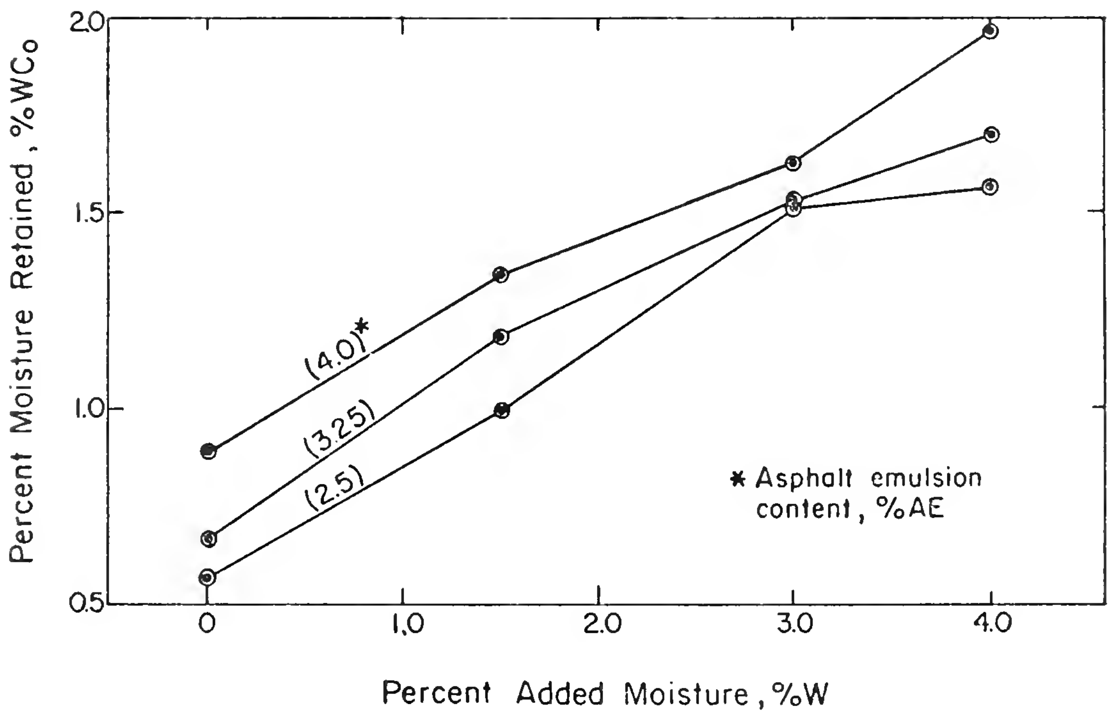
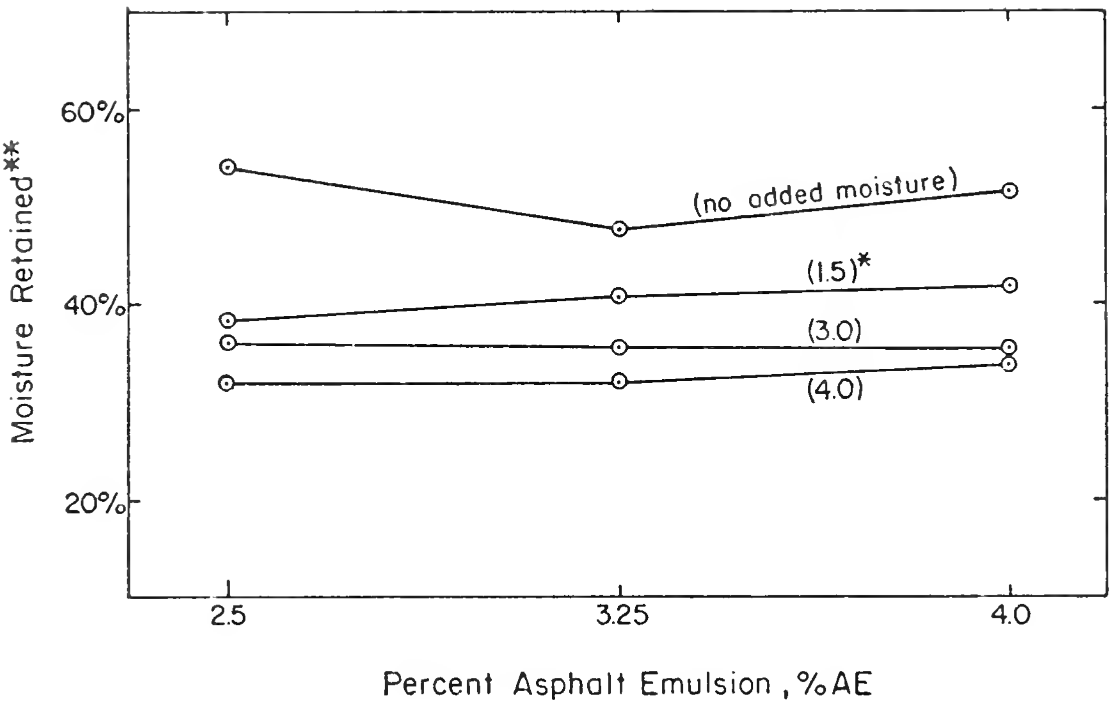


FIGURE 13, EFFECT OF ADDED MOISTURE AND ASPHALT EMULSION CONTENTS ON THE PERCENT OF RETAINED MOISTURE (one day air-dry curing)



Note:

* Percent added moisture, %W

** Expressed as percent of the original available moisture (added moisture + moisture portion in asphalt emulsion) = $\frac{WC_o}{\text{original moisture}} \times 100$

FIGURE 14, MOISTURE RETAINED AS A FUNCTION OF ASPHALT EMULSION RESIDUE AND ADDED MOISTURE CONTENTS

emulsion content and thus affects the properties and performance of the AETM especially at early curing time. However, after relatively long curing periods the difference in the percent retained moisture due to varying the initial added moisture will be relatively small.

Dry Unit Weight, γ_d

Both the dry and wet unit weights (γ_d and γ_w, respectively) of the different mix combinations were analyzed. The results of the analysis show that both the asphalt emulsion and added moisture contents together with their interaction significantly affect the values of γ_d and γ_w, at early curing condition. The wet unit weights had about the same trends as the dry unit weights with higher values of about 1 - 2 pounds per cubic foot for the different mix combinations. Most of the following discussion will deal with the dry unit weights with frequent reference to the γ_w whenever it is necessary.

Generally, increasing the asphalt emulsion content and/or increasing the added moisture content will result in increasing the dry unit weight of the samples (the same is true for γ_w). Figure 15, shows a general trend for the effect of these two factors on γ_d. These trends were obtained by averaging the results of all cells that corresponded to each level of the two factors under consideration. Also, the test results are presented in figure 16 in a contour form. It is of interest to note that the increase in γ_d is less at low ranges of %W (o and 1.5%) as compared to the high ranges of %W (3.0 and 4.0%). In addition, the interaction between %AE residue and %W significantly affect the γ_d values. This can be appreciated from reviewing figure 17.

A study of the unit weight of the specimens as a function of the total liquid that is available at time of testing (figure 18, a and b) shows that in general, the unit weights of the samples (γ_d and γ_w) increase with increasing percent total liquid. However, the trend differs depending on %AE and %W. At low added moisture contents, γ_d and γ_w will be obtained by increasing the %TL. In addition, the optimum total liquid that is required to provide maximum dry unit weight was about 4.5 to 5.0%, where as the optimum %TL that provides a maximum wet unit

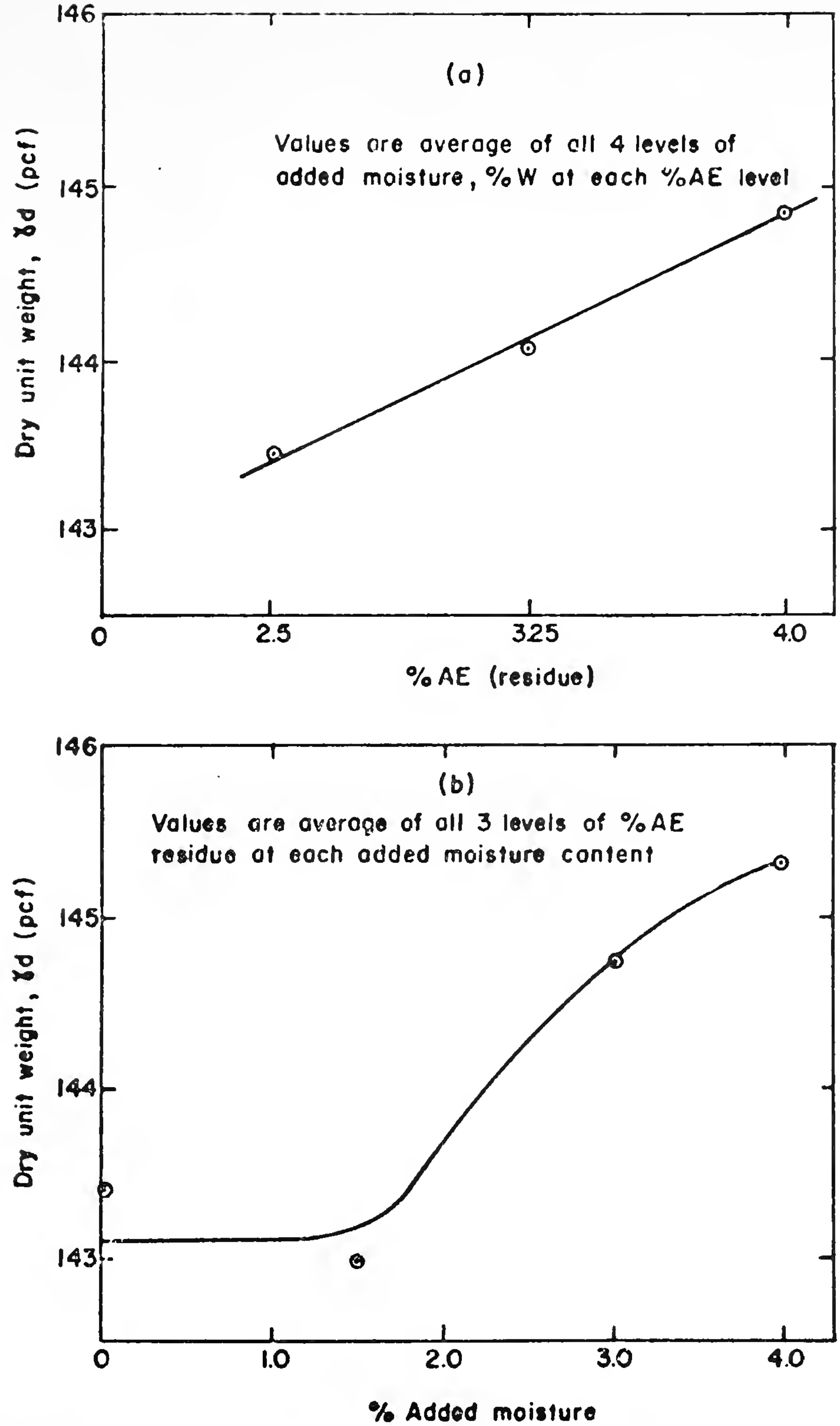


FIGURE 15, GENERAL EFFECT OF %AE (residue) AND % ADDED MOISTURE, %W ON DRY UNIT WEIGHT OF THE MIXTURES (MG aggregate & one day curing)

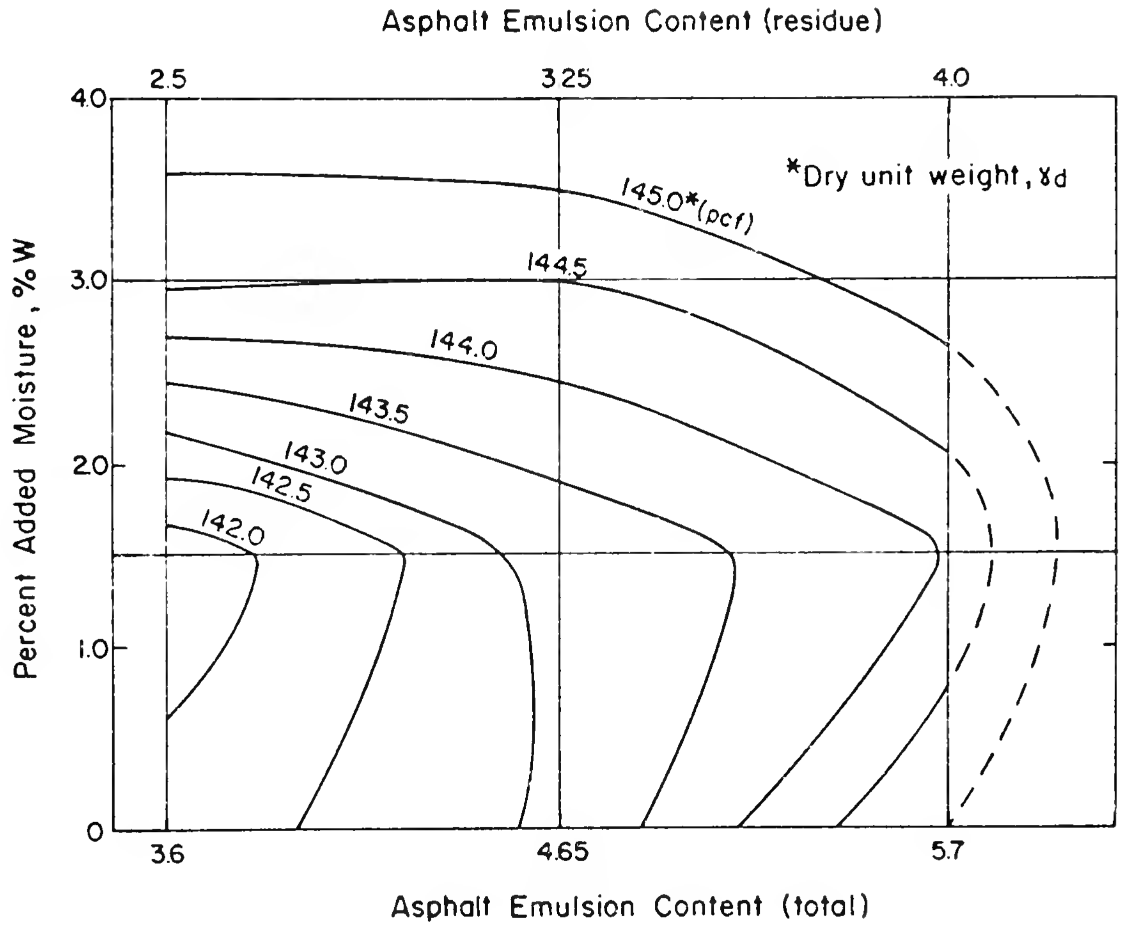


FIGURE 16, DRY UNIT WEIGHT, γ_d, AS A FUNCTION OF ASPHALT EMULSION AND ADDED MOISTURE CONTENTS (MG aggregate + one day curing)

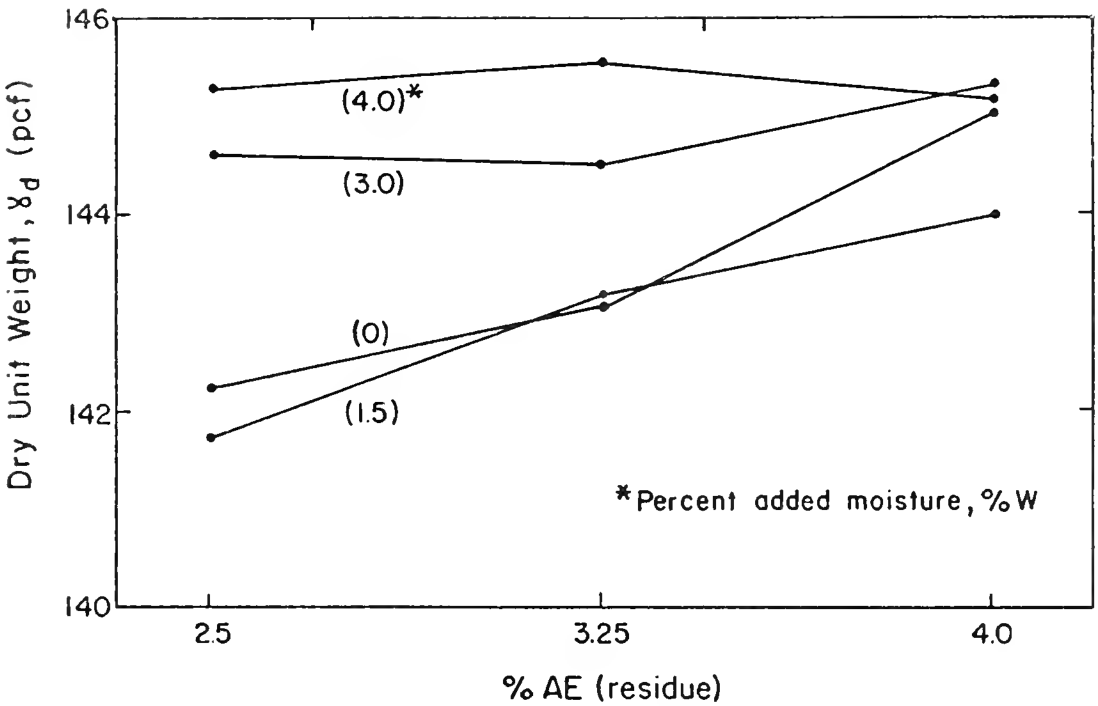
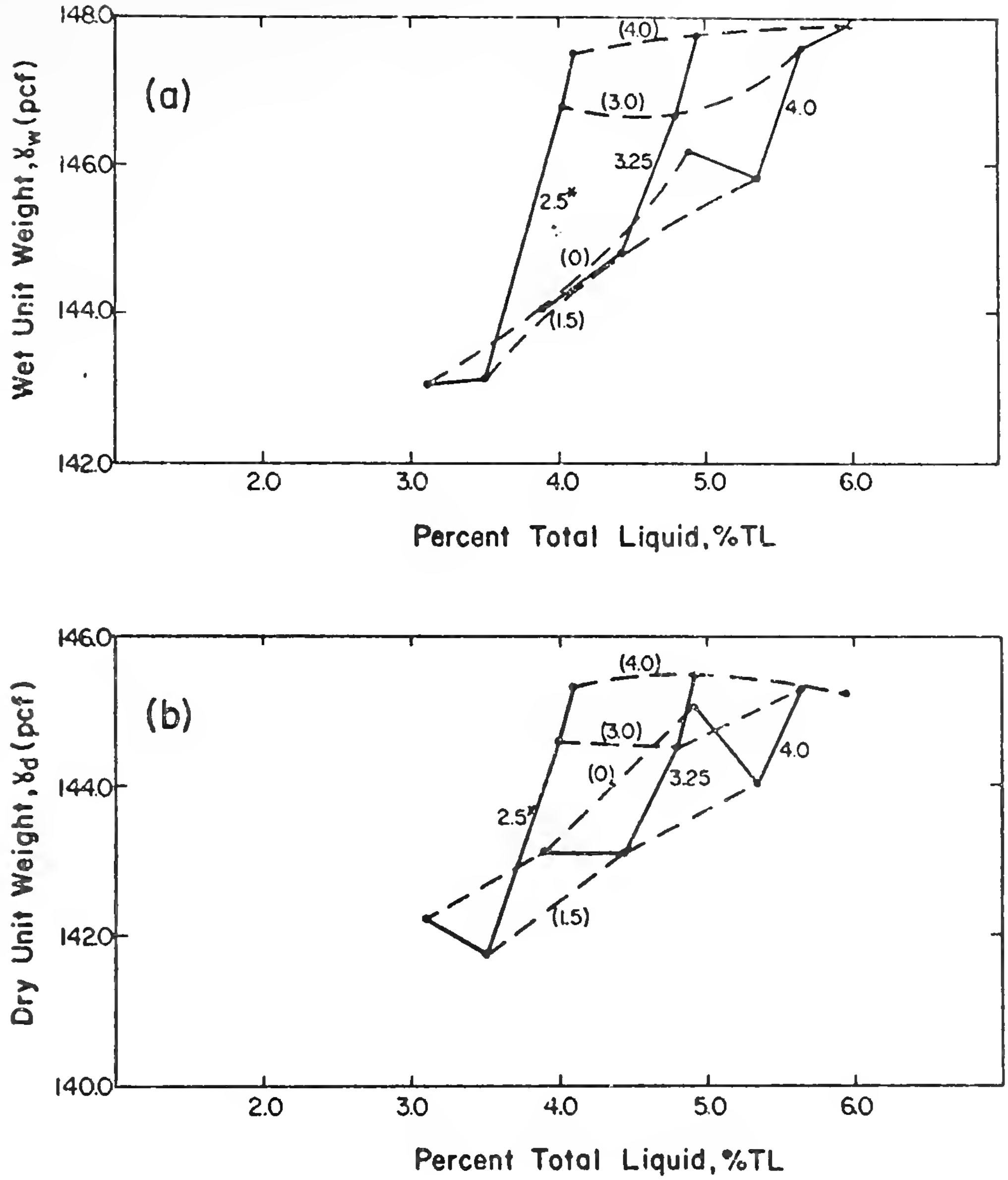


FIGURE 17, INTERACTION EFFECT OF ASPHALT EMULSION AND ADDED MOISTURE CONTENTS ON THE DRY UNIT WEIGHT (MG aggregate + one day curing)



<u>Note:</u>

—— For the same %AE residue

- - - For the same percent added moisture, %W

* Percent asphalt emulsion, %AE

( ) Percent added moisture, %W

FIGURE 18, RELATIONSHIP BETWEEN PERCENT TOTAL LIQUID AND UNIT WEIGHT FOR AETM; (a) FOR WET UNIT WEIGHT, γ_w (b) FOR DRY UNIT WEIGHT, γ_d

weight was about 5.5 to 6.0%. In other words, the optimum total liquid that is based on the dry unit weight parameter is about 1% less than that determined if based on the wet unit weight parameter.

Marshall Stability, P

The effect of the asphalt emulsion content on Marshall Stability was not significant. However, the initial added moisture and its interaction with the asphalt emulsion content were significant. This result draws attention to an important point that deals with the AETM properties at early curing conditions. The effect of asphalt emulsion content on the AETM stability is not apparent at early stages of curing which is mainly due to the nature of the asphalt emulsion present in the mix at this time. However, the significant effect of %AE becomes increasingly important during the curing process at which time the asphalt emulsion residue starts affecting gradually the mix properties. In addition, this result is attributed to the fact that the variations in Marshall Stability values due to the %AE factor were relatively small as compared to the within error term that accounts for the variation within each mix combination. Figure 19, presents the Marshall Stability values as a function of asphalt emulsion content and percent added moisture. The highest stability values were obtained for samples with no added moisture (it has to be noticed that about 0.2% moisture content was present in the aggregate). At 1.5% added moisture the highest P values were for samples with 3.25 %AE, however, the difference in stability is small. By increasing the added moisture content the samples with the low asphalt emulsion content (2.5%) displayed higher stability values.

The next step was to study the relationship between the Marshal Stability values of the mix and the percent total liquid available in the mix at time of test (figure 20). It is clear that the total liquid content, %TL, is an important factor that influences the response of the AETM (for a certain aggregate type and gradation). There exists an optimum liquid content that provides a mix with a maximum stability value. At a high asphalt emulsion content, a small percent of initial added moisture is adequate. However, for low asphalt emulsion contents,

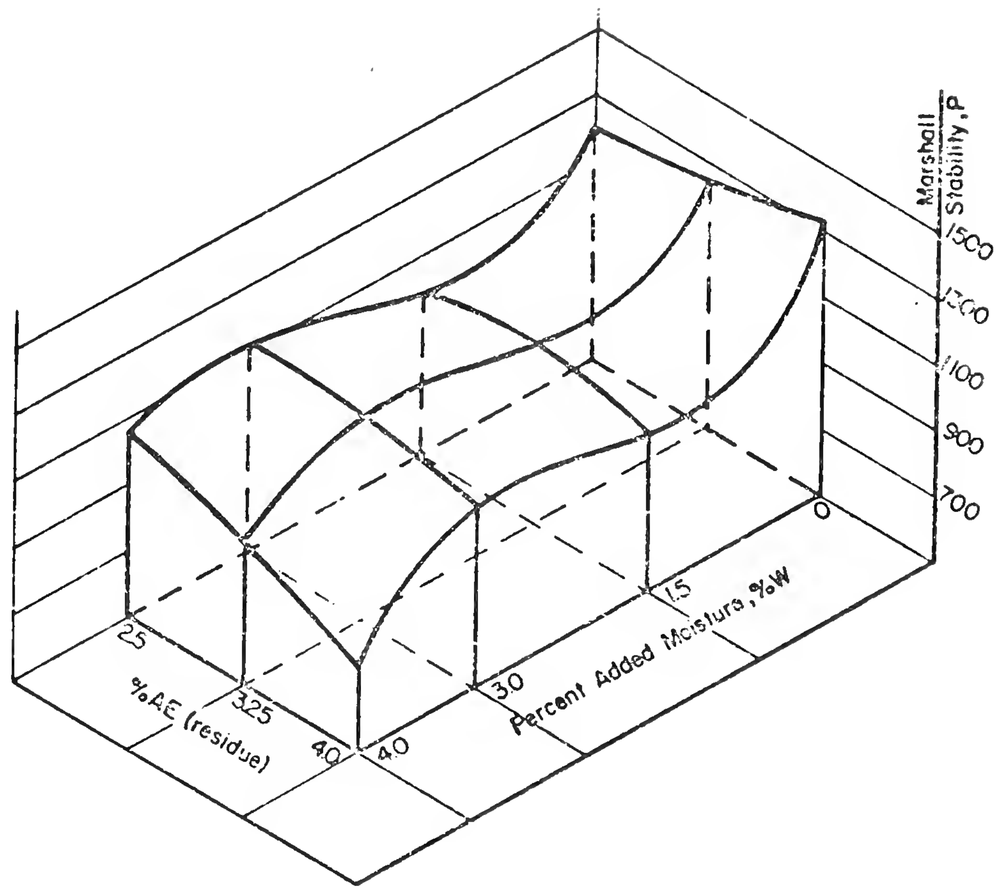


FIGURE 19, MARSHALL STABILITY AS A FUNCTION OF ASPHALT EMULSION AND ADDED MOISTURE CONTENTS (MG aggregate; one day air-dry curing)

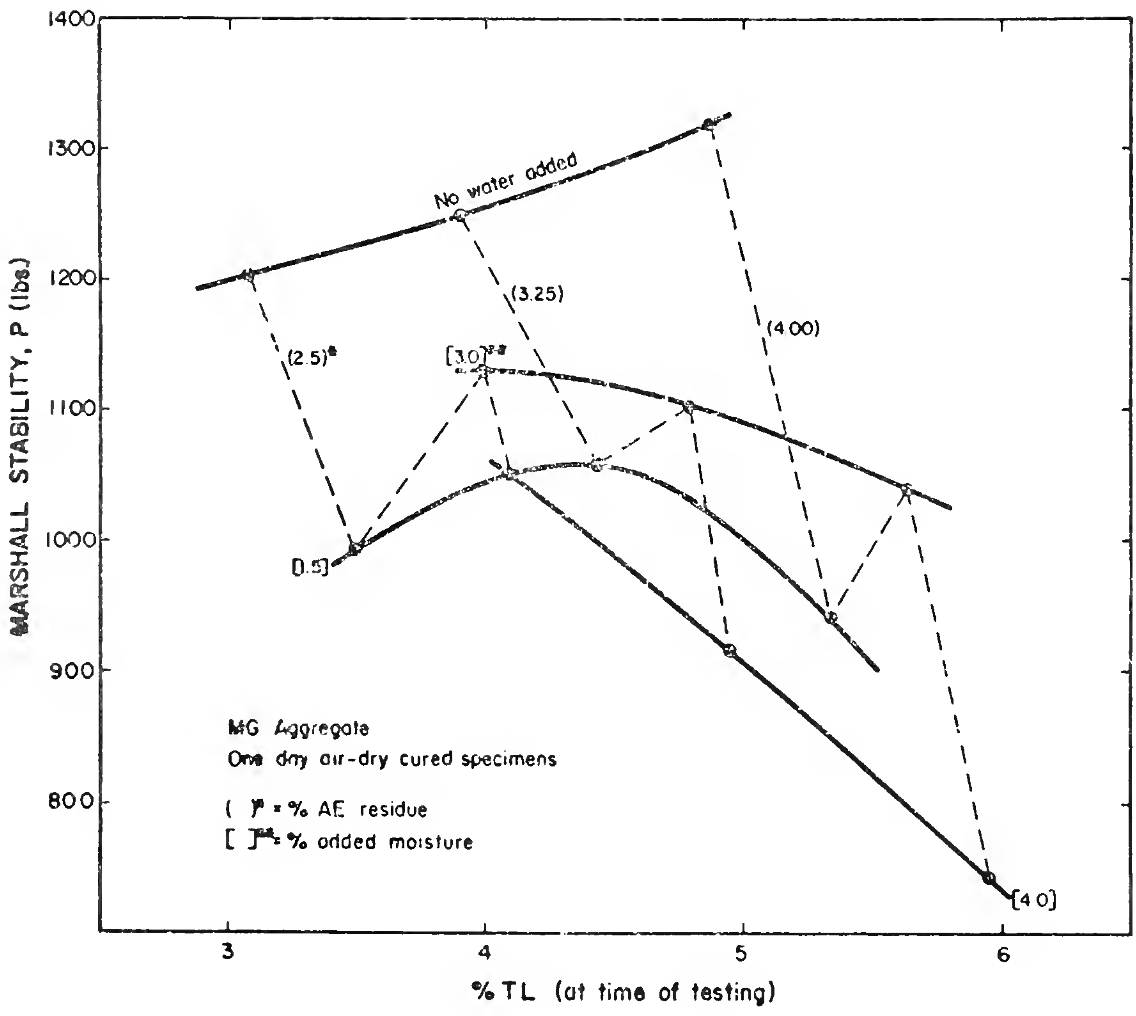


FIGURE 20, MARSHALL STABILITY AS A FUNCTION OF PERCENT TOTAL LIQUID, (%TL), ASPHALT CONTENT (%AE), AND PERCENT ADDED MOISTURE (%W)

increasing the amount of added moisture up to a certain limit will improve the properties of the mix. From Figure 20 it can be seen that at no added moisture the highest stability was obtained by using 4% AE residue. At 1.5% added moisture, a drop in stability occurred for samples with 4% AE, at the same time samples with 3.25% AE content provided the highest stability values. By increasing the added moisture more than 1.5% the samples with 2.5% AE gave the highest stability values which is mainly due to the fact that at this stage both samples that contained 3.25% and 4% AE resulted in a mix with a total liquid content more than the optimum and consequently a reduction in stability values was observed. The optimum liquid content (at time of testing) and after excluding the samples with no added moisture was in the range of 4.0 to 4.5%.

The amount of total liquid in the sample plays an important role in the properties of the AETM. Also, there exists an optimum liquid content at time of testing that provides a region within which the mix will reach a maximum density and/or stability. However, it has to be emphasized that the asphalt emulsion content and the percent added moisture (consequently, the percent retained moisture, $\%WC_0$) which are the components of the total liquid have to be evaluated and studied because of their significant role in influencing the AETM properties.

Marshall Flow, F

The Flow values ranged from 6 to 11 (0.01" units). Both the asphalt emulsion and added moisture contents and their interaction have a significant effect on the flow values. However, it has to be emphasized that the significance of the interaction term was mainly due to the wide range of the added moisture content levels especially the no added moisture (0%) level. When the levels of %W were reduced to just 2 levels, as in the later parts of the study, this interaction effect was not significant.

In general it was observed that the flow values increased by increasing the asphalt emulsion content. Also, by increasing the percent added moisture the flow values increased. However, mixes with no added

moisture exhibited a higher flow values than those with 1.5% added moisture. This could be appreciated by reviewing the AETM system components and their interrelationship at an early condition of curing. By adding moisture to the mix, the mix components will behave mainly as an untreated mixture (at early curing condition) with a relatively high resistance to deformation due to the friction forces among aggregate particles. On the other hand, when no initial water was added to the mix, the AETM behaves in a different manner under the effect of load. The friction between the particles will be less and the nature of the asphalt emulsion role will predominate.

Percent Air Voids and Total Voids

The percent air voids ($\%V_A$) and total voids ($\%V_T$) at time of testing are directly related to the percent total liquid (Figure 21). $\%V_A$ and $\%V_T$ decrease as the percent total liquid increase. Also, increasing the amount of asphalt emulsion in the mix decreases the air voids and total voids that are available. The total voids ranged from 8% to 12.5%, where as the percent air voids ranged from 4% to 11% depending upon the asphalt emulsion and added moisture contents.

Marshall Stiffness (S_m) and Marshall Index (I_m)

Both asphalt emulsion content and added moisture content together with their interaction significantly affected the S_m and I_m values. However, the asphalt emulsion content showed a greater influence on S_m values than the added moisture content. Generally, by decreasing the %AE both the Marshall Stiffness and Index will increase as the mix becomes less plastic and the slope of the load deformation curve will be steeper. The same trend holds for the effect of percent added moisture. Figure 22 shows the general trend for I_m values (which is of the same character as S_m but with a relatively higher values). It has to be recognized that the interaction between the asphalt emulsion and added moisture content is of importance and that the relation is not of a simple nature. This interaction effect is apparent in Figure 23, in which both S_m and I_m values are presented with regard to the respective %AE and %W. Marshall

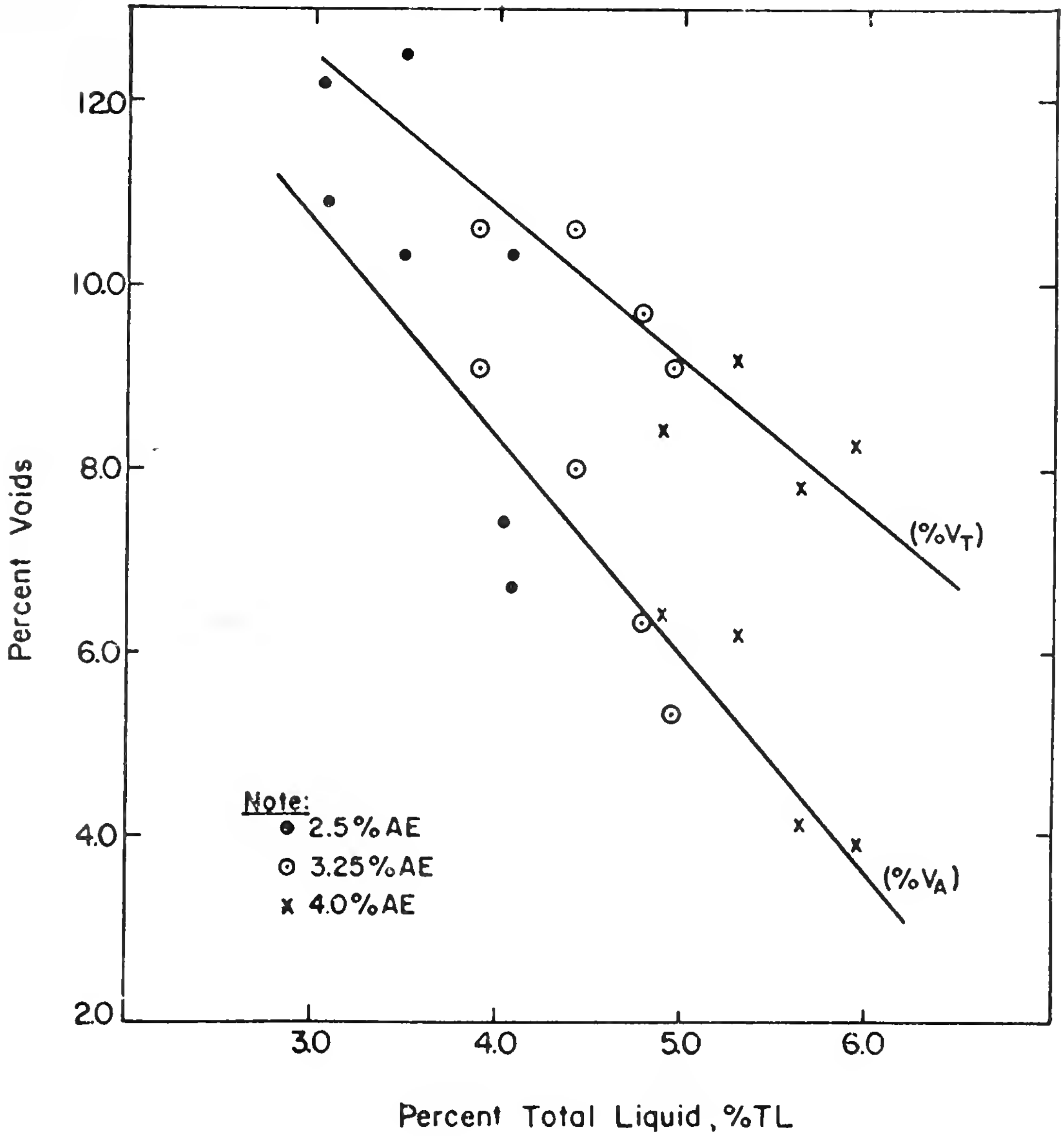
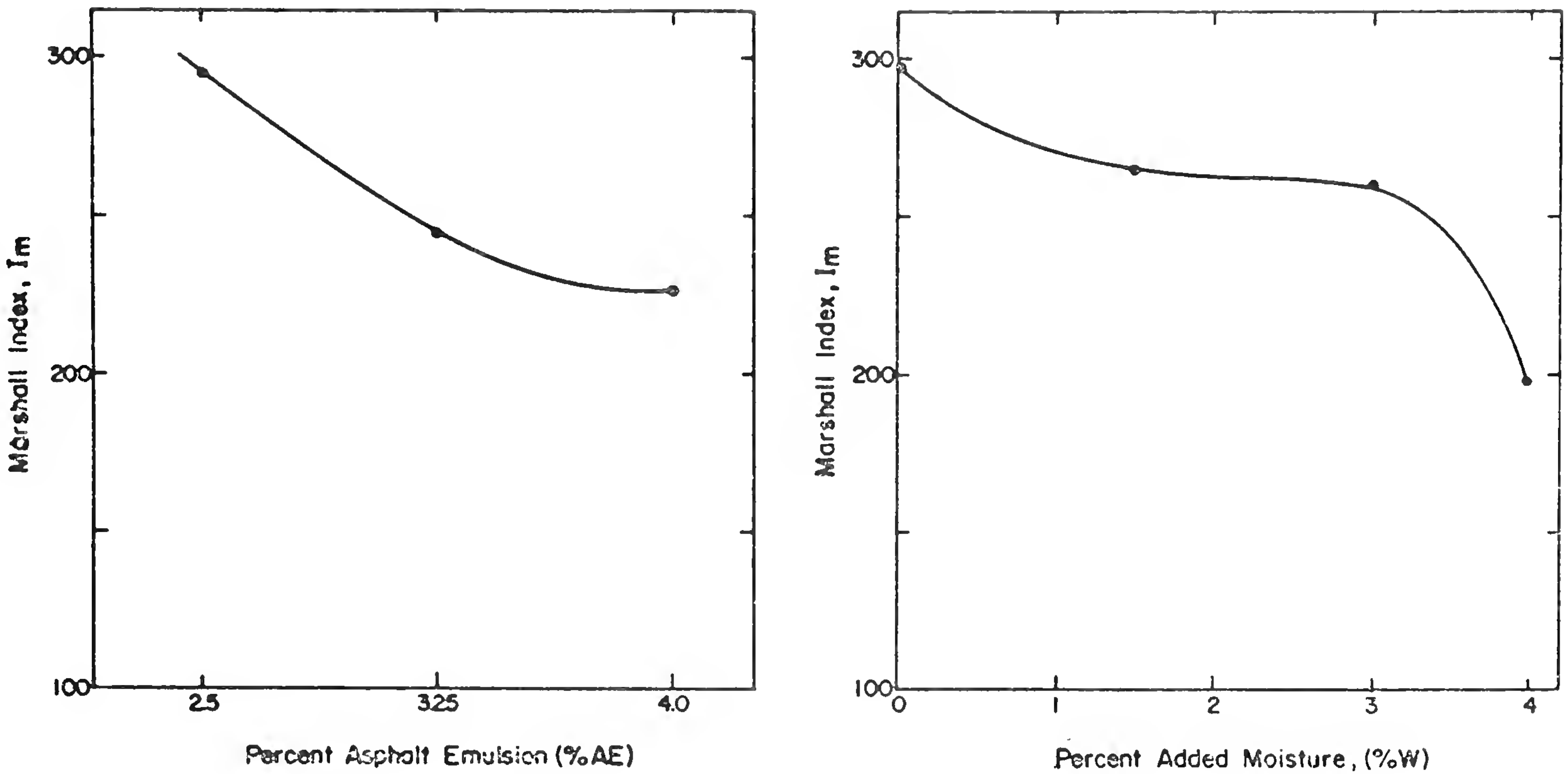


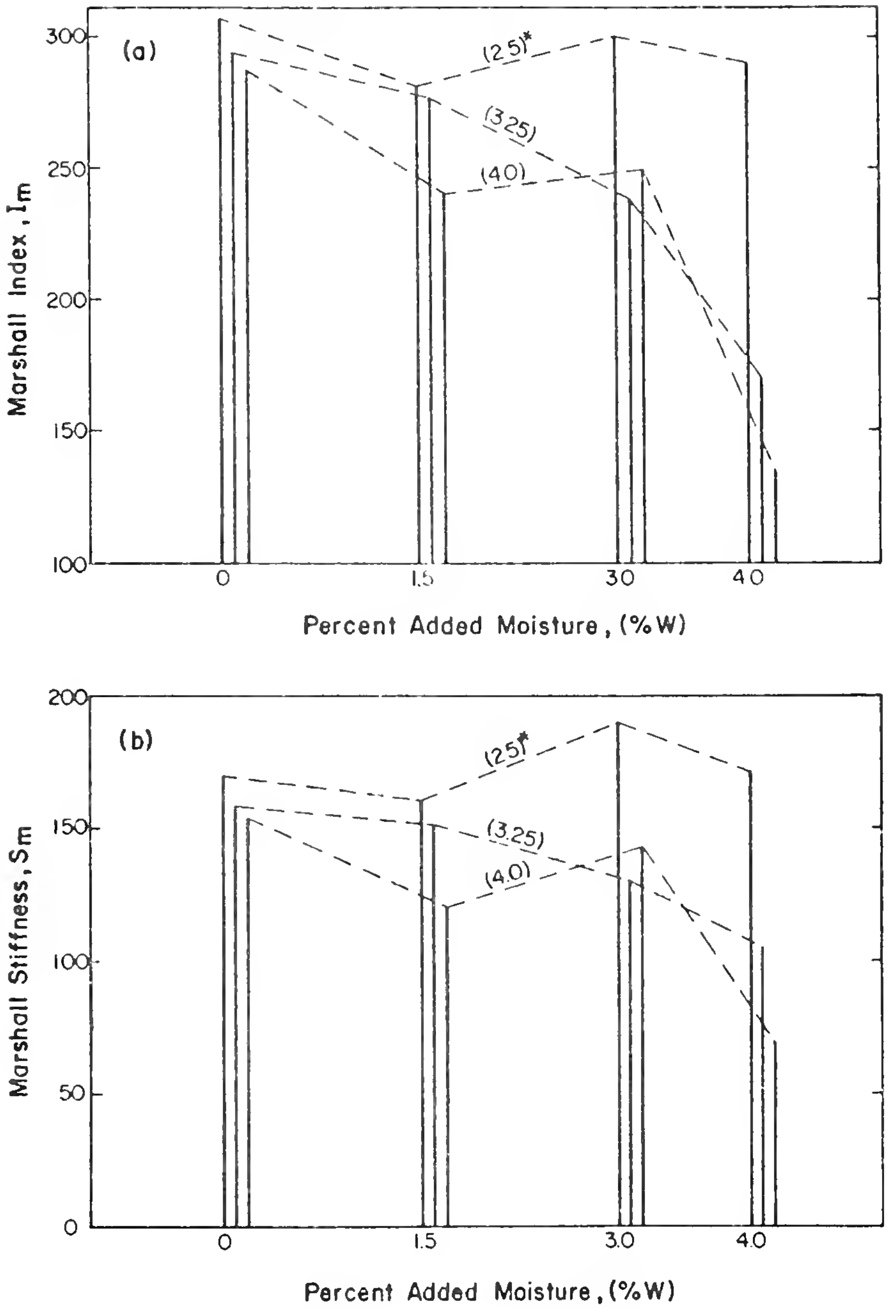
FIGURE 21, PERCENT AIR VOIDS (%V_A), AND TOTAL VOIDS (%V_T) AS A FUNCTION OF PERCENT TOTAL LIQUID (%TL) AND ASPHALT EMULSION CONTENT (%AE)



Note:

1- MG-aggregate
2- One day curing at room temperature
3- The data points represent the average of all levels of the other factor

FIGURE 22, GENERAL TREND FOR THE EFFECT OF ASPHALT EMULSION AND ADDED MOISTURE CONTENTS ON THE MARSHALL INDEX, I_m



Note:

1- MG-aggregate
2-One day curing at room temperature
3-( )* percent asphalt emulsion residue

FIGURE 23, INTERACTION EFFECT BETWEEN ASPHALT EMULSION AND ADDED MOISTURE CONTENT ON: (a) MARSHALL INDEX, AND (b) MARSHALL STIFFNESS

Index trends are about the same as Marshall Stiffness trends but have higher values due to the nature of the parameters themselves. The Index values represent the slope of the linear portion of the load-deformation curve, where as the Stiffness values represent the slope of the line connecting the initial or starting loading point with the failure point.

The total liquid content at time of testing is of importance when one considers its affect on the performance of the AETM. Both Marshall Stiffness (S_m) and Index (I_m) values decrease by increasing the percent total liquid (Figure 24). This effect is more apparent when one uses the Index values as a measure for the performance. It should be noted that in this part of the study the change in percent total liquid for a certain asphalt emulsion content is mainly due to using a different added moisture content. It has to be emphasized that the percent asphalt emulsion is of great importance and it has to be considered together with the percent total liquid in the evaluation. It can be seen from the graph that even though all the %AE residues provided the same trends, each one of the asphalt emulsion contents provided its unique significant effect. Also, it is of interest to note the relatively small changes in I_m and S_m for low asphalt emulsion content (2.5%) mixes.

Water Sensitivity Test Results

The resistance of AETM to water damage was evaluated using the Asphalt Institute water sensitivity test (5). The tests were conducted for mix combinations that contained 3% initial added moisture at the three different levels of asphalt emulsion residue contents (see Table 2).

Table 6, presents the results of the water sensitivity tests for the one day air-dry cured specimens. Also, Figure 25 depicts the Marshall stability values for the soaked specimens as compared to the dry stability values. The Marshall stability vs. asphalt emulsion content for the soaked specimens indicated a peak stability value at 3.25% AE residue while the dry test results provided, as discussed before, an increase in stability with decreasing %AE residue. However, it must be noted that the differences in stability values were not of a significant nature. In Figure 26, where Marshall stability values for both the dry and soaked conditions are presented as a function of the percent total liquid

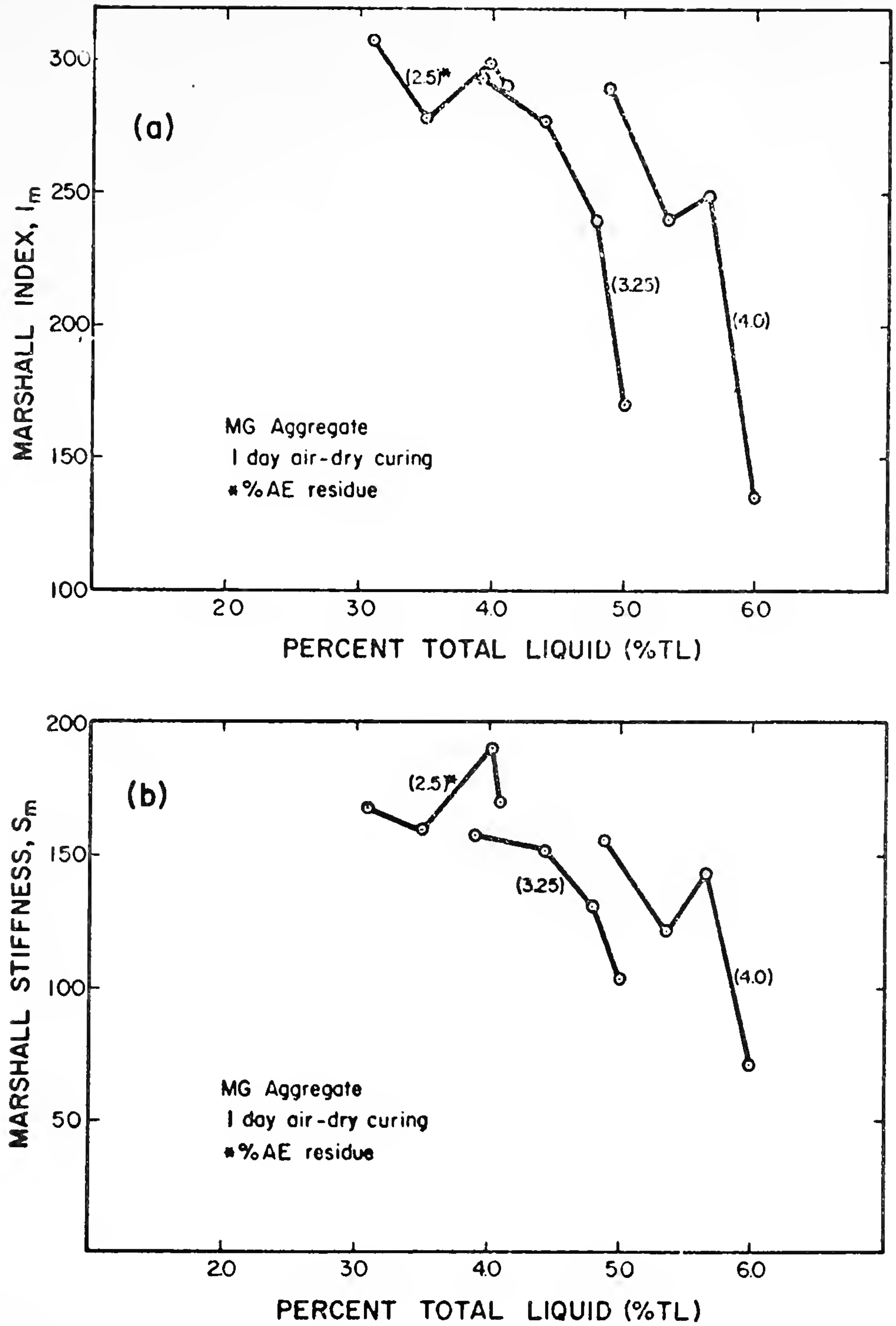


FIGURE 24, EFFECT OF PERCENT TOTAL LIQUID (%TL) ON; (a) MARSHALL INDEX, AND (b) MARSHALL STIFFNESS

TABLE 6: WATER SENSITIVITY TEST RESULTS (MG AGGREGATE, 3% ADDED MOISTURE, AND ONE DAY AIR-DRY CURING)

Property \ %AE (residue)	2.50	3.25	4.00
% retained P	41%	58	57
% retained S_m	57%	67	48
% retained I_m	50%	68	44
WC_{o1}*	1.67	1.69	1.89
WC_{o2}**	4.26	3.57	3.02
%MA†	2.59	1.88	1.13
%TL††	6.76	6.82	7.02

* Percent moisture retained in the dry sample before the water sensitivity test.

**Percent moisture retained in the soaked sample after the water sensitivity test.

† Percent moisture absorption (moisture picked-up).

††Percent total liquid at time of testing for the soaked specimens.

Note: All percentages expressed as percent by weight of dry aggregate.

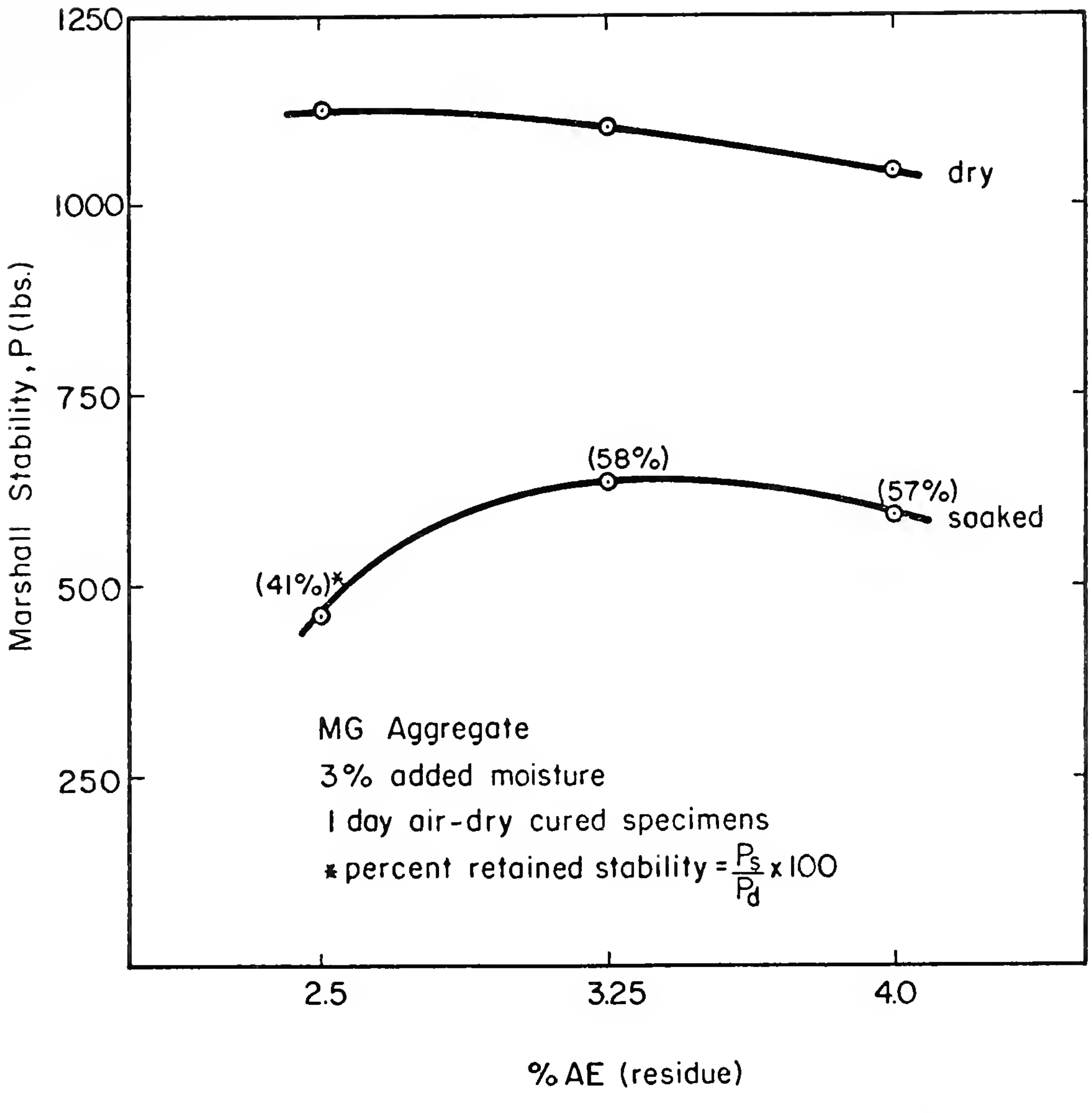


FIGURE 25, MARSHALL STABILITY FOR DRY AND SOAKED SPECIMENS

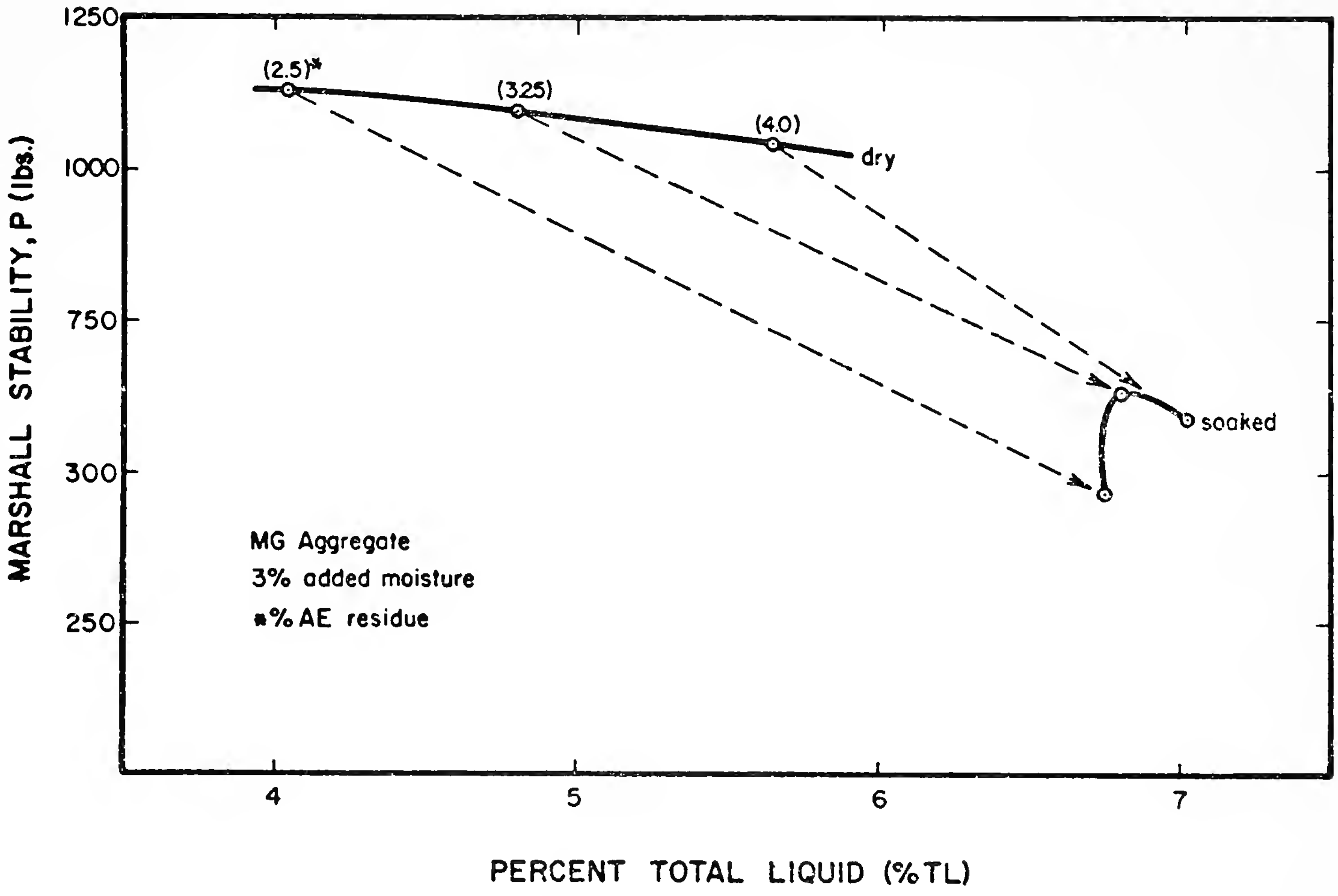


FIGURE 26, MARSHALL STABILITY AS A FUNCTION OF PERCENT TOTAL LIQUID FOR DRY AND SOAKED SPECIMENS

at time of test, the effect of the water sensitivity test (WST) is more pronounced. A large drop in stability for samples with low asphalt emulsion content were accompanied by a large amount of moisture absorption (moisture pick-up). The effect on the samples that contained 3.25% and 4.0% asphalt residue was not of the same magnitude.

Figure 27 presents the Marshall stiffness and Index values for both the dry and soaked conditions, in which the percent retained stiffness and Index values are dependent on the asphalt mulsion residue content.

From the results of these tests it could be concluded that:

1. Dry test results provided higher stability values for samples with low asphalt residue contents. However, the test results for the soaked specimens show a larger drop in the stability values for samples with low asphalt emulsion content as compared to test results for samples with higher asphalt emulsion content.
2. For the same initial added moisture, by increasing the asphalt emulsion residue content from 2.5% to 4% increased the percent retained stability from 40 to 57%.
3. The percent of moisture absorption decreased with an increase in the asphalt emulsion content, which is a main factor that influences the properties of the AETM.

These results are mainly due to the fact that for the same aggregate type and gradation, increasing the asphalt emulsion content provides more bonding and adhesion to the aggregate and relatively less air voids which reduces the effect of water in the mix properties.

From the previous discussion it is clear that evaluating the AETM properties in both the dry condition, and after introducing the effect of water is of importance and that a study of the response parameters of the mix in the dry condition is not enough for providing an adequate understanding and control of the mix properties. It is believed that controlling the mix properties based on the water sensitivity results is a major part in the AETM design. More detailed discussion of the effect of water on the properties of AETM will be presented in the following chapters, each relative to the factor under consideration.

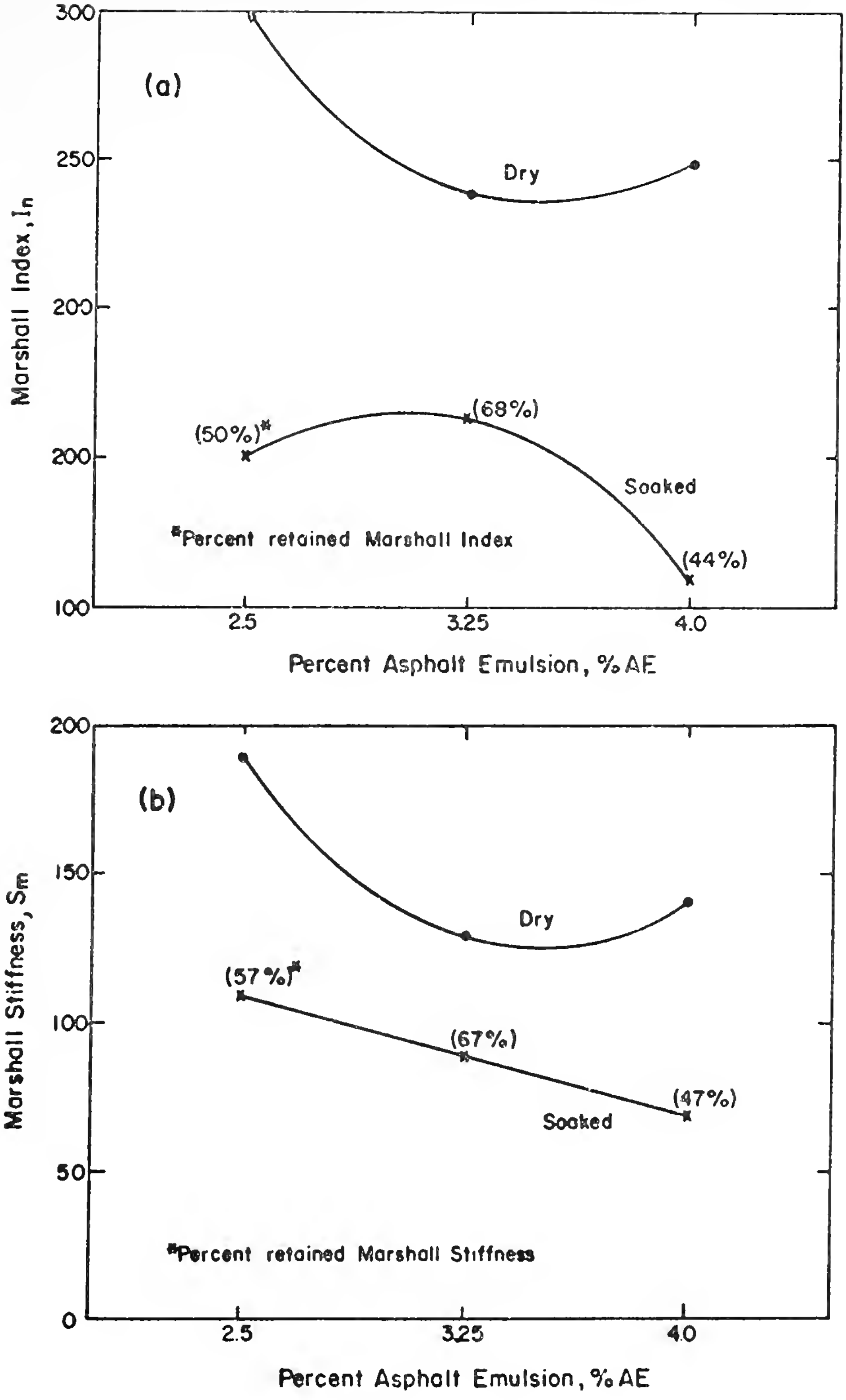


FIGURE 27, DRY AND SOAKED INDICES (a) MARSHALL INDEX
(b) MARSHALL STIFFNESS

Summary of Results

The evaluation of AETM properties at an early curing condition (one-day curing at room temperature), resulted in a number of significant results. The following summary of the important findings pertains to the effect of asphalt emulsion residue and added moisture contents influencing the properties of AETM at early curing condition. It should be emphasized that the results of this part of the study (and those of the following parts) are limited to the materials and tests that were used.

1. The percent of retained moisture at time of testing is affected by %AE residue and %W, with the initial added moisture, %W having a greater bearing on the amount of retained moisture.
2. Both %AE and %W and their interaction significantly affect the dry and wet unit weights of AETM. The optimum total liquid that provides a maximum dry density is lower than that required to provide a maximum wet density.
3. The effect of %AE on Marshall stability is not significantly apparent at early curing conditions. This is due to the nature of the AETM component system at this stage of curing. However, the effect of AE residue content will be enhanced through the curing process.
4. Percent total liquid at time of testing is an important factor that affects the AETM properties. However, it has to be combined with the %AE in the evaluation.
5. As expected, the air voids ($\%V_A$) and total voids ($\%V_T$) available in the mix are directly related to %TL, %AE, and $\%WC_o$.
6. The Marshall Stiffness (S_m)and Index (I_m) parameters show a unique and definite trend that depend on the percent total liquid, asphalt emulsion content, and amount of added moisture (for a specific aggregate type and gradation). S_m and I_m values decreased while increasing the percent of total liquid at time of testing. However, at low AE contents the stiffness parameters were relatively unaffected by the added moisture content as compared to AETM specimens with relatively higher AE content.

In addition, while the stability values were not sensitive to changes in %AE at early curing condition, the stiffness parameters showed a significant response to changing the percent asphalt emulsion residue.

7. The water sensitivity test has to be an integral part of the design procedure for AETM. It provides an insight for the understanding and control of the mix properties under one of the conditions that should be of main concern in the mix design and construction of AETM. In addition, by comparing, for example, the relationships between the stability and %AE for both the dry and soaked specimens, an interesting result is observed. The trends of the dry test Marshall stabilities decreased with an increasing %AE, while the soaked test results provided a typical pattern of a maximum stability at a corresponding optimum %AE. Using the two conditions (dry and soaked) in the mix design would provide a more realistic and better selection of the AETM components.

CHAPTER VII: EFFECT OF CURING, ASPHALT EMULSION, AND ADDED MOISTURE CONTENTS ON AETM PROPERTIES

Introduction

The effect of curing time, amount of asphalt emulsion, and added moisture contents on the properties of AETM were evaluated in this phase of the study. The introduction of the curing factor in the analysis was intended to provide an adequate evaluation of the trends of AETM properties through the curing process, and also to provide a better understanding of the role of the AETM components, %AE and %W during the curing process. The same aggregate gradation (MG) was used in this phase of the study. It should be noted that the effect of aggregate gradation will be presented in the next chapter of this investigation.

Table 7, presents the factorial design of this phase of the study. This partial design was extracted and presented separate from the factorial design of the overall study (Table 3) for the sake of clarity and completeness of the presentation for this phase of the study. Three levels of the asphalt emulsion content (%AE), two levels of the added moisture content (%W), and five levels of curing were used. MG aggregate gradation was used in this phase. Three replicates were tested in each mix combination. In addition, two specimens were tested for the water sensitivity analysis in each one of the pre-selected cells (see Table 3).

The AETM properties were analyzed within the framework of a fixed-effect randomized complete block design, RCBD (2). This was done to remove a source of variation due to the effect of blocks from the error term. The curing time corresponded to the blocks of RCBD. Since all tests had to be completed at a specified curing time before proceeding to another curing time, a restriction on randomization was caused. As a result of this restriction, the effect of curing on various evaluated response variables could not be tested for significance. However, in some cases an indirect or conservative test for the effect of curing was utilized.

TABLE 7, FACTORIAL DESIGN FOR STUDY OF FACTORS AFFECTING AETM PROPERTIES (phase 2 ; design I)

Additives	Curing time + condition	% W	%AE (residue): 2.5 (Agg. Gradation: M.G.)	3.25	4.0
(NO P.C.)	1day	1.5%	X	X	X
		3%	(X)	(X)	(X)
	3	1.5	X	X	X
		3	(X)	(X)	(X)
	5	1.5	X	X	X
		3	X	X	X
	7	1.5	X	X	X
		3	X	X	X
	ult. cond.	1.5	X	X	X
		3	(X)	(X)	(X)

<u>Note:</u>

X - dry test

O - water sensitivity test

Analysis of Results

The following analysis of variance model was used to evaluate the AETM response variables:

$$Y_{ijk\ell} = \mu + C_i + \delta_{(i)} + A_j + AC_{ij} + W_k + CW_{ik} + AW_{jk} + CAW_{ijk} + \varepsilon_{(ijk)\ell}$$

where

$Y_{ijk\ell}$ = measured or response variable

μ = overall true mean.

C_i = true effect of curing time.

$\delta_{(i)}$ = restriction error, random, NID (o, σ^2), completely confounded with the effect of the ith curing time.

A_j = true effect of the asphalt emulsion content, %AE.

W_k = true effect of the added moisture content, %W.

$\varepsilon_{(ijk)\ell}$ = true random error, NID (o, σ^2).

The other terms denote the interactions among the factors C, A, and W. All main factors are fixed. The subscripts assume the values:

$i = 1, 2, 3, 4, 5$

$j = 1, 2, 3$

$k = 1, 2$

$\ell = 1, 2, 3$

The original data for the various response variables were tested for homogeneity of variance. The results of Foster-Burr test are shown in Table 8. The assumption of homogeneity of variance was accepted for five of the dependent variables (γ_d, γ_w, $\%WC_o$, P, and F). However, a logarithmic transformation was applied to the data of S_m and I_m to meet the assumption of homogeneity of variance (see Table 8). Therefore, the analysis of variance, ANOVA, was performed on the original data for the first five variables and on the transformed data for S_m and I_m.

Table 9, presents a summary of the ANOVA for AETM response variables. In addition, a typical analysis of variance table is shown in Table B2, in the appendices. It is of interest to note that the ANOVA results that were obtained by using the original data of S_m and I_m are the same as those obtained when using the transformed data (Table 9). This is

TABLE 8: FOSTER-BURR TEST FOR HOMOGENEITY OF VARIANCE

Response Variable	Degree of Freedom	No. of Samples	$Q_{statistic}$	Homogeneity of Variance
Y_d	2	30	.077	accept*
Y_w	2	30	.072	accept*
$\%WC_o$	2	30	.111	accept**
P	2	30	.070	accept*
f	2	30	.094	accept*
S_m	2	30	.229	reject**
I_m	2	30	.205	reject**
log S_m	2	30	.107	accept**
log I_m	2	30	.107	accept**

* $Q_{2,30,0.01} = 0.100$

**$Q_{2,30,0.001} = 0.124$

TABLE 9, SUMMARY OF ANOVA RESULTS FOR AETM PROPERTIES (phase 2 ; design I)

Source of Variation \ Response Variables		γ_d	γ_w	$\%WC_o$	P	F	S_m	$\log_{10}S_m$	I_m	$\log_{10}I_m$
C		—	—	S^+	S^+	—	S^+	S^+	S^+	S^+
A	%AE	S	S	S	S	S	S	S	S	S
W	%W	S	S	S	S	S	N.S.	N.S.	N.S.	N.S.
CA		N.S.	S	S	S	N.S.	S	S	S	S
CW		S	S	S	N.S.	S	N.S.	N.S.	N.S.	N.S.
AW		S	S	N.S.	S	N.S.	S	S	S	S
CAW		N.S.	N.S.	S	S	S	S	S	N.S.	N.S.

Note:

1 - S = Significant at $\alpha = 0.05$
2 - NS = Not significant at $\alpha = 0.05$
3 - — = No test available, due to restriction on randomization
4 - + = Indirect test, see discussion on page 74.

mainly due to the insensitivity of the ANOVA to small violations of the assumptions of normality and homogeneity of variances when dealing with a fixed effect model with equal sample size (8). As a result, the discussions and conclusions presented herein that pertain to S_m and I_m are based on the original data, bearing in mind that the only reason is that the original and transformed data gave the same results.

Due to the restriction in randomization, the curing time factor could not be tested. It is recognized that a replication of the experiment would have allowed a valid test on curing time, however, for this experiment only one replication was feasible. However, the effect of curing time was tested for some of the response variables as can be seen in Table 9. This was based on two reasons: (a) the significance of curing time factor "C" was very high (tested at $\alpha = 0.001$) and (b) the mean square values attributed to "C" were at the same order or higher than those attributed to the other main factors. These two reasons provided a base for assuming that the error mean square due to the blocking effect, for all practical purposes, is not significant or equal to zero and consequently a test on the curing time factor was conducted for some of the response variables.

The following sections present a study of each one of the AETM response variables. This will be followed by a presentation of the water sensitivity test results that correspond to this phase of the study.

Percent of Moisture Retained in the Sample, $\%WC_o$

All the main factors, two factor, and three factor interactions affected the percent of moisture retained significantly, except the interaction between the asphalt emulsion content and the added moisture content which was not significant. Figure 28 shows the relationship between percent moisture retained ($\%WC_o$) and %AE, %W, and curing time. For a specific %AE, the percent retained moisture depends on the added moisture content and curing time. The higher the added moisture content the higher the retained moisture. The difference in $\%WC_o$ due to using 3% and 1.5% added moisture decreased as the curing time increases. At the same time, for a specific initial added moisture the retained

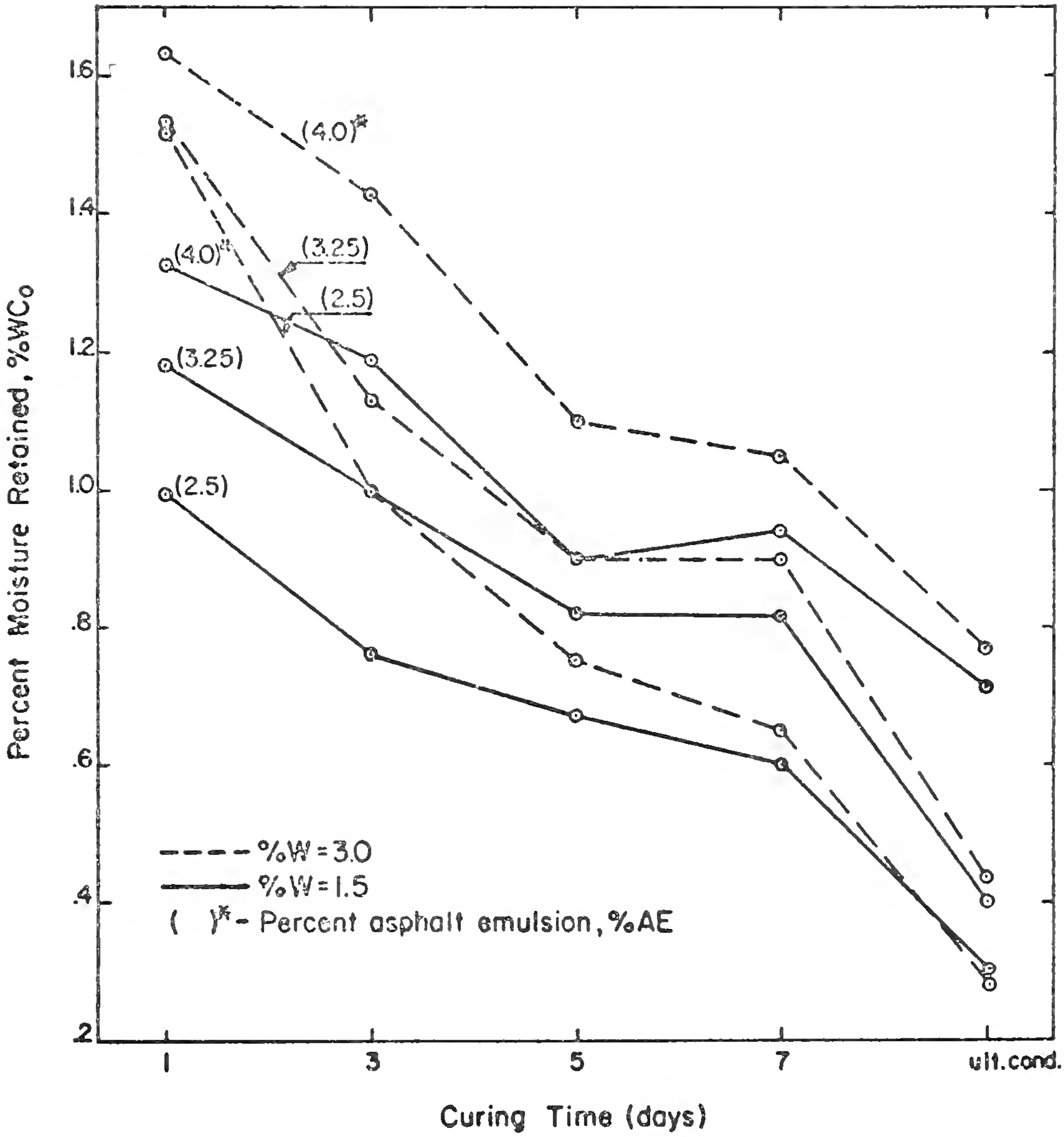


FIGURE 28, RELATIONSHIP BETWEEN PERCENT RETAINED MOISTURE AT TIME OF TESTING (%WC_o), CURING TIME, %AE RESIDUE, AND PERCENT ADDED MOISTURE (%W)

moisture increased with an increase in the percent asphalt emulsion in the mix. However, the difference in $\%WC_0$ due to the use of different asphalt emulsion contents was about the same throughout the different curing periods.

Dry Unit Weight, γ_d

All factors significantly affected the dry and wet unit weights. However, the CAW interaction term was not significant. Figure 29 shows the dry unit weight values relative to the %AE, %W and curing time. It is of interest to note the significant effect of the percent asphalt emulsion and added moisture on the AETM dry density. Also, the effect of the initial moisture on the dry unit weight (γ_d) decreased through the different curing periods. This occurred as a result of the reduction in variation in the amount of moisture retained due to changing the initial added moisture throughout the curing process. In other words, the effect of varying the percent added moisture on the amount of retained moisture decreased through the curing process and consequently its effect on the dry density was reduced.

Marshall Stability, P

In the previous chapter (Chapter VI) it was shown how the asphalt emulsion and added moisture contents and consequently the percent total liquid (%TL) affected the stability of the AETM specimens. In this phase of the study an additional examination of the effect of these factors on AETM stability was performed, with emphasis on the effect of changing %TL through the curing process.

From the ANOVA, all factors significantly affected the Marshall stability values except that of the interaction between added moisture content and curing time which was not significant. It is of importance to compare the effect of percent asphalt emulsion on Marshall stability to the results of the previous phase of the study which was conducted for the early curing condition. The %AE significantly affected the stability values at the different curing stages in spite of the non significant role of %AE at early curing condition. Figure 30 presents

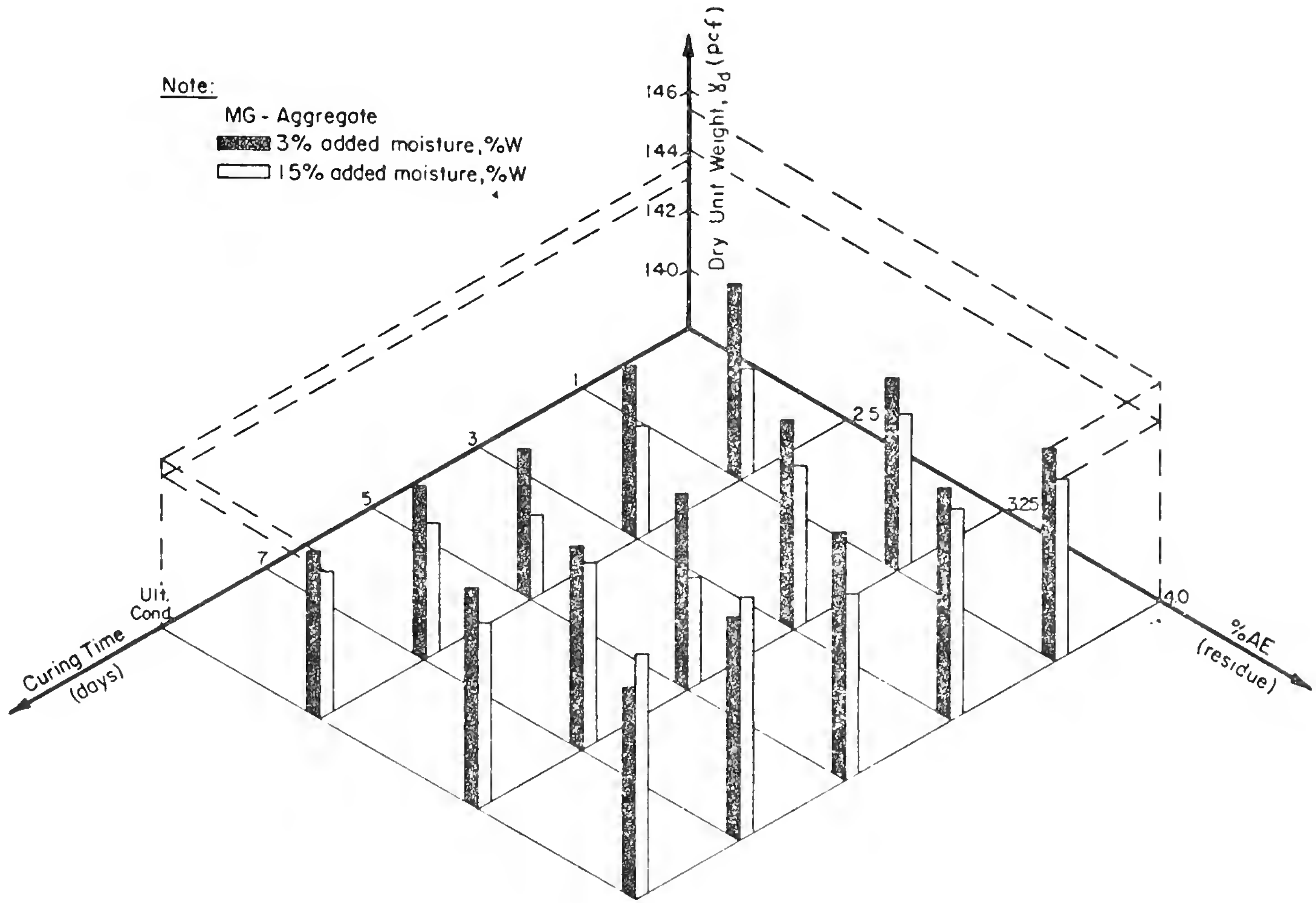


FIGURE 29, DRY UNIT WEIGHT VALUES (γ_d), AS A FUNCTION OF CURING TIME, ASPHALT EMULSION, AND ADDED MOISTURE CONTENTS

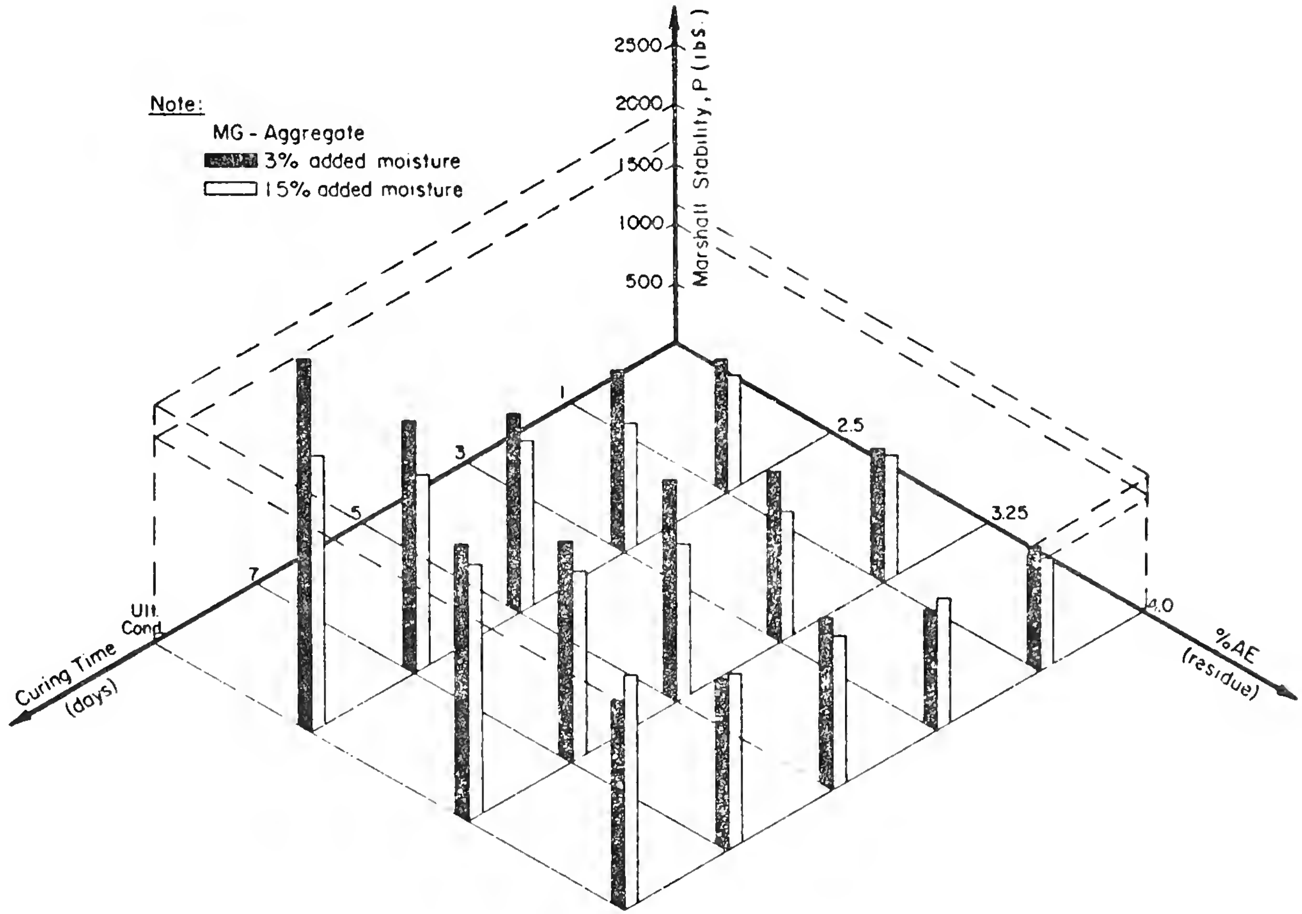


FIGURE 30, STABILITY VALUES AS A FUNCTION OF CURING TIME, ASPHALT EMULSION, AND ADDED MOISTURE CONTENTS

the trend in stability values as a function of curing time, %AE, and %W. At the early curing condition, the effect of %AE, and percent added moisture was practically not apparent. However, their effect became evident during the curing process. Also, the gain in stability through the curing process depended on the asphalt emulsion content. The lower the asphalt emulsion content in the mix the more gain in stability will be attained through the curing process. The role of percent added moisture was more pronounced for AETM that contained a low asphalt emulsion content.

The relationship between the stability and percent total liquid at the time of testing is presented in Figure 31. The dashed lines represent the stability vs. %TL trends for the different %AE and %W. The change in %TL was attained through the curing process. For a certain mix combination, the Marshall stability values increase appreciably with curing and the resulting decrease in the percent total liquid. In the graph, the data points that represent one day curing condition and ultimate curing were connected with the solid lines for each one of the two added moisture levels. This provided the stability vs. %TL trends, for a specific curing period, through changing the %AE. At the early curing condition (one day curing at room temperature) the difference in P is small. However, the change in P is more pronounced at the ultimate curing condition.

The use of percent total liquid at time of testing as one of the controlling factors that affect the AETM response parameters is of significance but provides only a general trend. Each of the components which constitutes the total liquid (that is %AE, and %W) plays an important role in the performance of the mix and has to be studied and controlled. For the same percent total liquid, different combinations of %AE and $\%WC_o$ provide different response values.

Marshall Flow, F

Flow values for the different mix combinations at the different curing periods ranged from 4.5 to 11.5 units (0.01 inch units). In general, increasing the asphalt emulsion content relatively increased

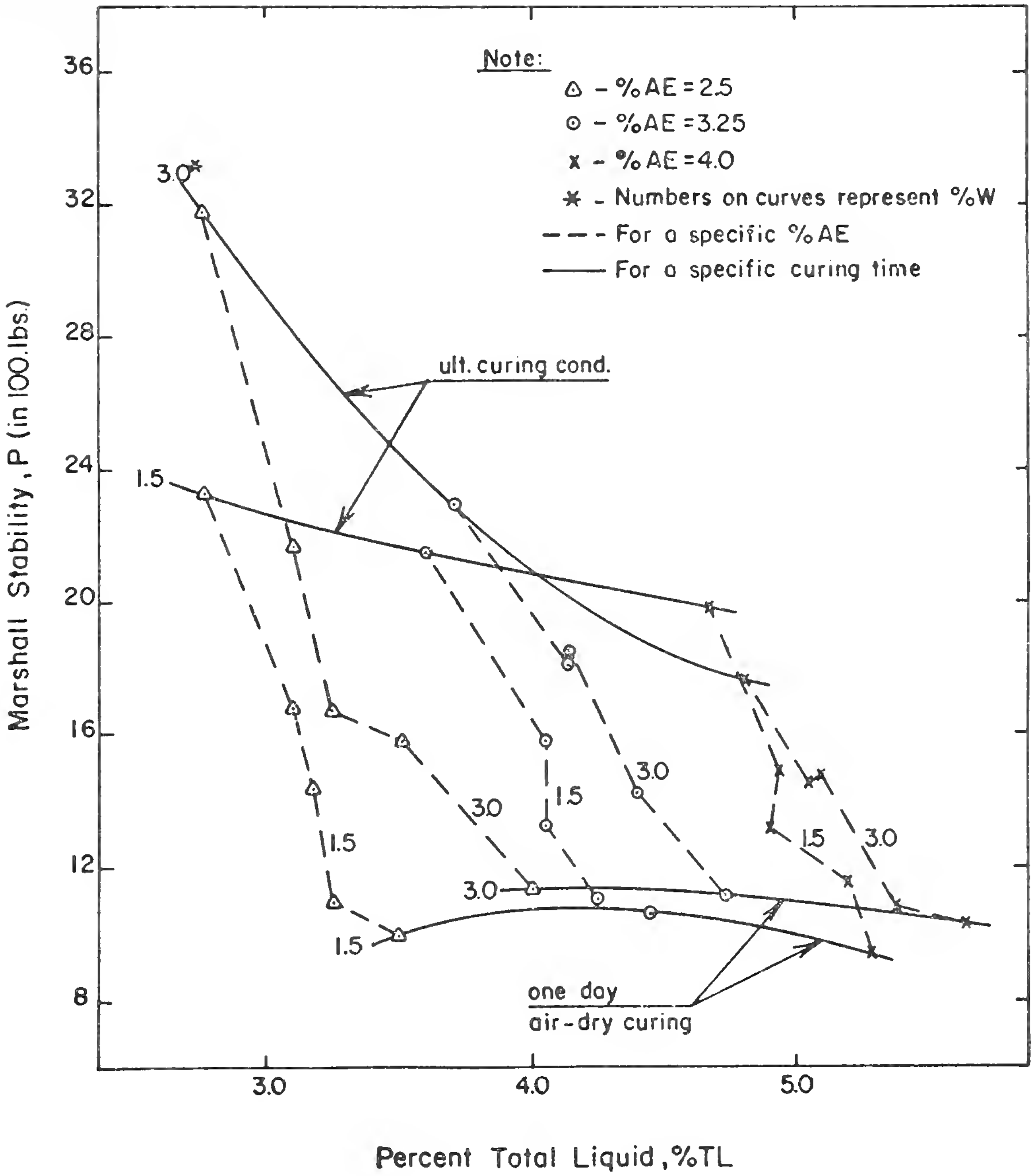


FIGURE 31, EFFECT OF PERCENT TOTAL LIQUID (%TL) ON MARSHALL STABILITY (P) - (MG aggregate)

the flow values. Besides, for a certain mix combination, flow values increased with the progress in curing i.e. the more curing time allowed, the less the amount of moisture will be retained in the mix and consequently it behaves under the load in a more cohesive manner. However, mixes with 3% initial added moisture provided higher flow values than that obtained by using 1.5% added moisture at any curing time except that after one day curing (Figure 32).

Air Voids and Total Voids

Both the air voids ($\%V_A$) and total voids ($\%V_T$) are directly related to the percent total liquid available at the mix which in turn is a function of %AE, $\%WC_o$. Data shown in Figure 33 are for the average values of all mix combinations at the different curing periods. A linear relationship exists between each of the $\% V_A$ and $\% V_T$ and %TL. The correlation coefficient was -0.96 and -0.87 for the $\%V_A$ and $\%V_T$, respectively.

In addition, by examining the data in a stratified manner, Figure 34 presents the interaction effect of %AE, %W, and curing time on both the air voids and total voids.

Marshall Stiffness (S_m) and Marshall Index (I_m)

It was pointed out earlier in the chapter, that the ANOVA results for both the original and transformed data for each one of these parameters were the same. Therefore, all the discussion will be dealing with the original data, namely, S_m and I_m. The results of the analysis of variance are shown in Table 9.

The asphalt emulsion content factor and its interaction with the other factors (curing, and added moisture content) affected these two indices significantly. However, the added moisture content (%W), and its interaction with curing were not significant. Figure 35(a) and (b), presents the test results of S_m and I_m, respectively, as a function of %AE, %W, and curing time. Larger amounts of %AE in the mix resulted in lower S_m and I_m values. S_m and I_m which are a function of the load-deformation characteristics of the AETM, vary with curing time. Through

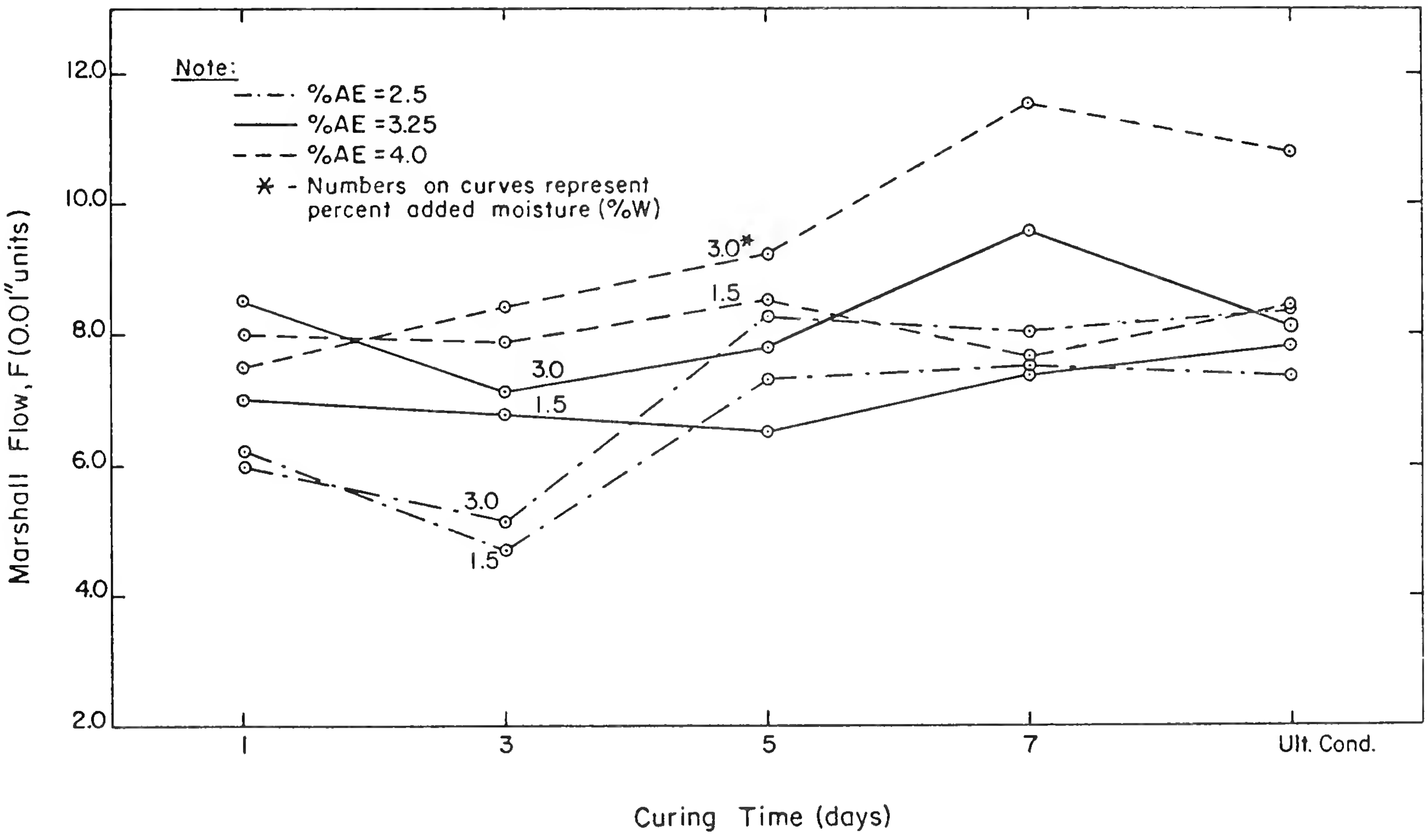


FIGURE 32, MARSHALL FLOW VALUES (F) AS RELATED TO CURING TIME, %AE, AND %W - (MG aggregate)

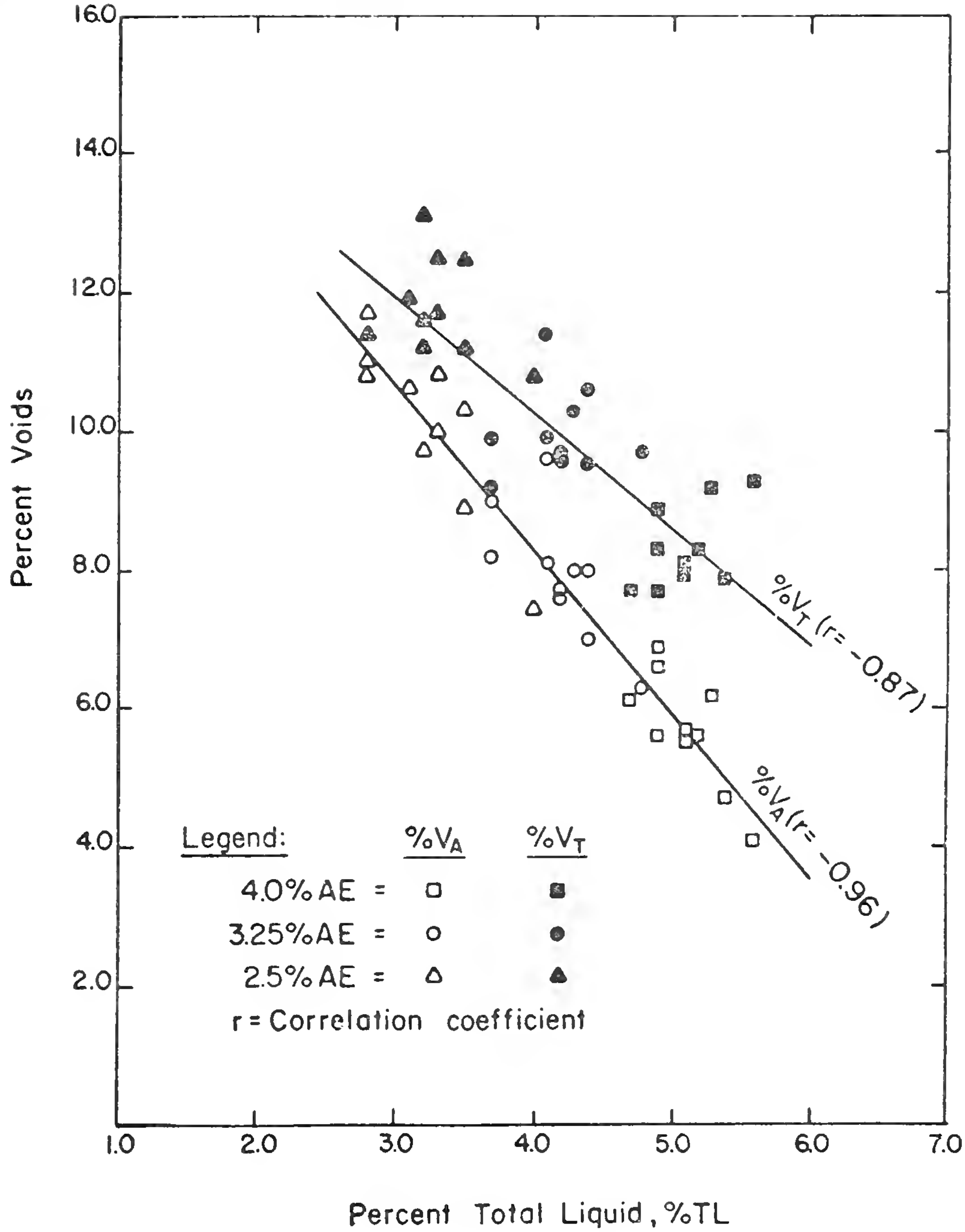


FIGURE 33, PERCENT AIR VOIDS (%V_A) AND PERCENT TOTAL VOIDS (%V_T) AS A FUNCTION OF PERCENT TOTAL LIQUID (%TL) - (MG aggregate; 5 curing periods)

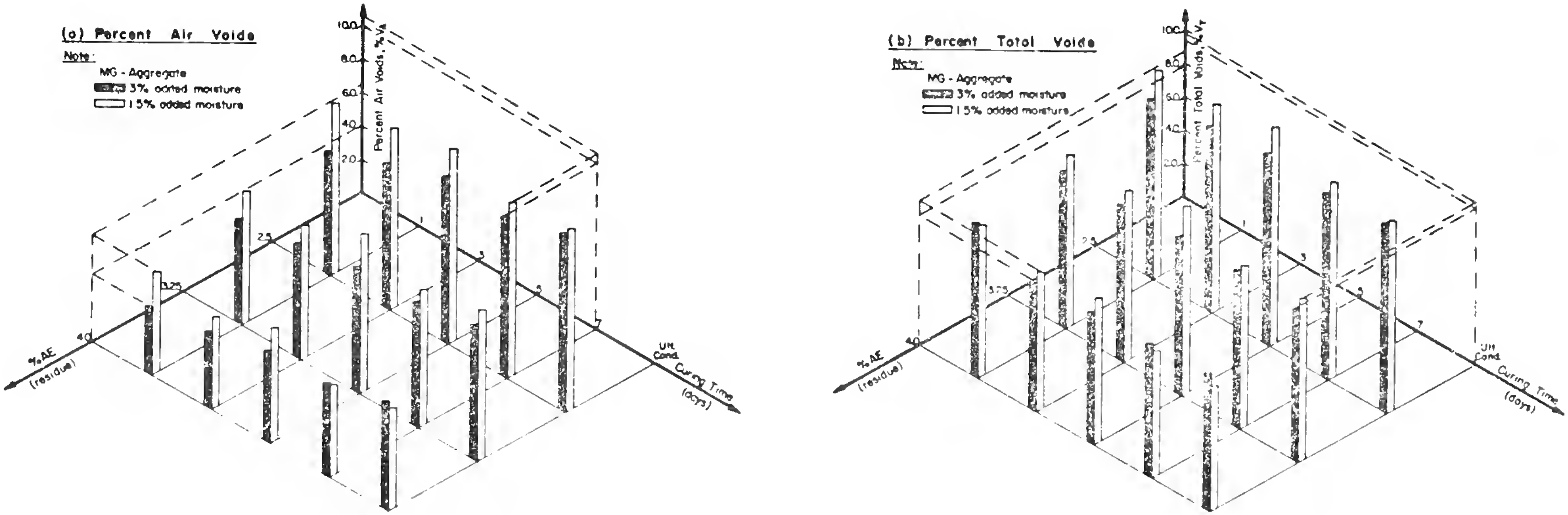


FIGURE 34, EFFECT OF INTERACTION AMONG CURING TIME, ASPHALT EMULSION, AND ADDED MOISTURE CONTENTS ON: (a) PERCENT AIR VOIDS ($\%V_A$) AND (b) PERCENT TOTAL VOIDS ($\%V_T$)

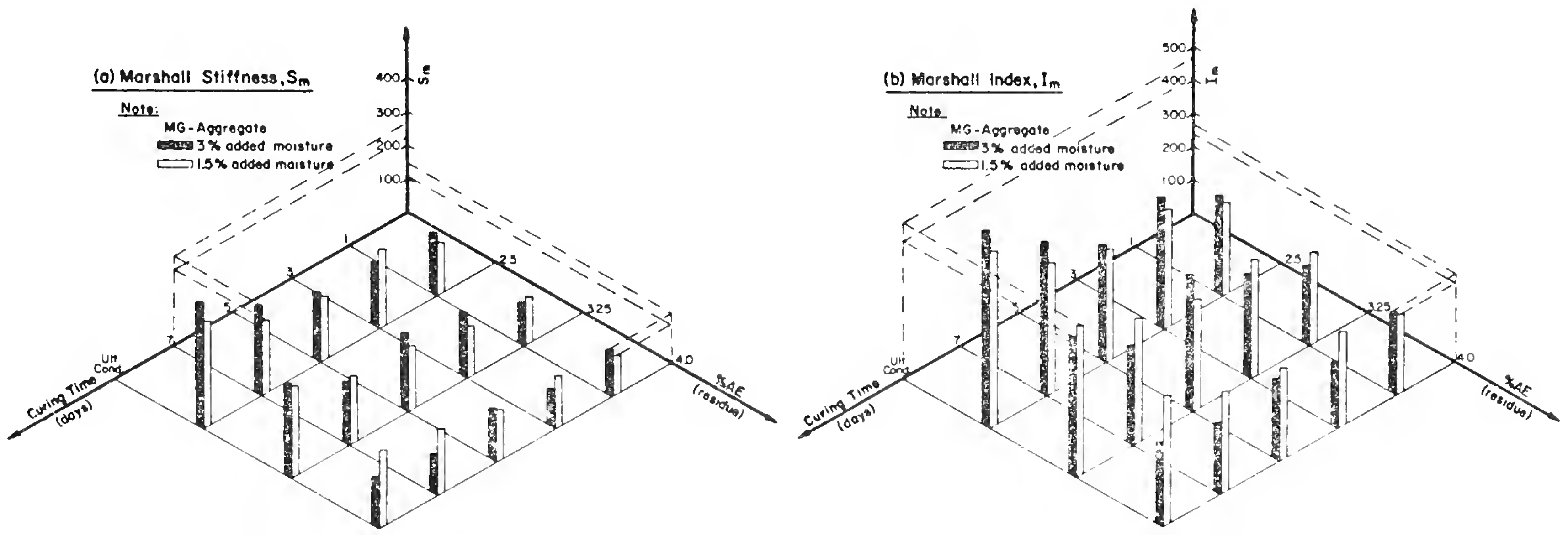


FIGURE 35, EFFECT OF CURING TIME, ASPHALT EMULSION, AND ADDED MOISTURE CONTENTS ON MARSHALL INDICES ; (a) MARSHALL STIFFNESS (S_m), AND (b) MARSHALL INDEX (I_m)

the curing process, the stiffness indices of the AETM increase. The increase or gain in S_m and I_m through the curing process is relatively larger and more pronounced for AETM that contain low percentages of asphalt emulsions. As can be seen from the graphs, for 4% asphalt emulsion specimens the change in S_m or I_m is not pronounced and it looks as if it did not change through the curing. By decreasing the asphalt emulsion content in the mix the gain in the stiffness indices increase (compare the trends of 2.5%, and 3.25 to those of 4% AE.)

For mixes that contained 2.5% asphalt emulsion, the Marshall Index values, I_m, were higher when 3% added moisture was used than when using 1.5%. However, for AETM that contained a relatively high percentage of asphalt emulsion (4%) the trend is reversed providing higher I_m values when using 1.5%W as compared to 3%W. Study of the I_m trends for mixes that contained 3.25% asphalt emulsion content, (which represents approximately a mix at the middle between the dry and wet side of the AETM mix composition), it could be noticed that the effect of the added moisture changes course during the curing process depending mainly on the %TL that is available in the mix.

It should be noticed that the relatively higher variation in S_m trends as opposed to I_m results is due to the fact that S_m values depend on measuring two variables P and F, where as the I_m values depend on measuring just one variable which is the slope of the linear portion of the load-deformation curve.

Figure 36, presents the S_m values as a function of %TL. In Figure 36(a) the change in %TL was obtained by changing %AE in the mix for the two curing periods, where as in Figure 36(b) the change in %TL was attained through the curing process for each asphalt emulsion residue content and using 3% added moisture. The main purpose of presenting the data in this form is to provide a better understanding of one of the fundamental concepts that deal with the role of percent total liquid in the properties of the AETM. In general, the stiffness parameters of the mix depend on %TL which decreases as the %TL increases. Also, by using high percentages of AE, the S_m values change with changing %TL in a random manner within a narrow band (see Figure 36(b)). Through the curing process the S_m values

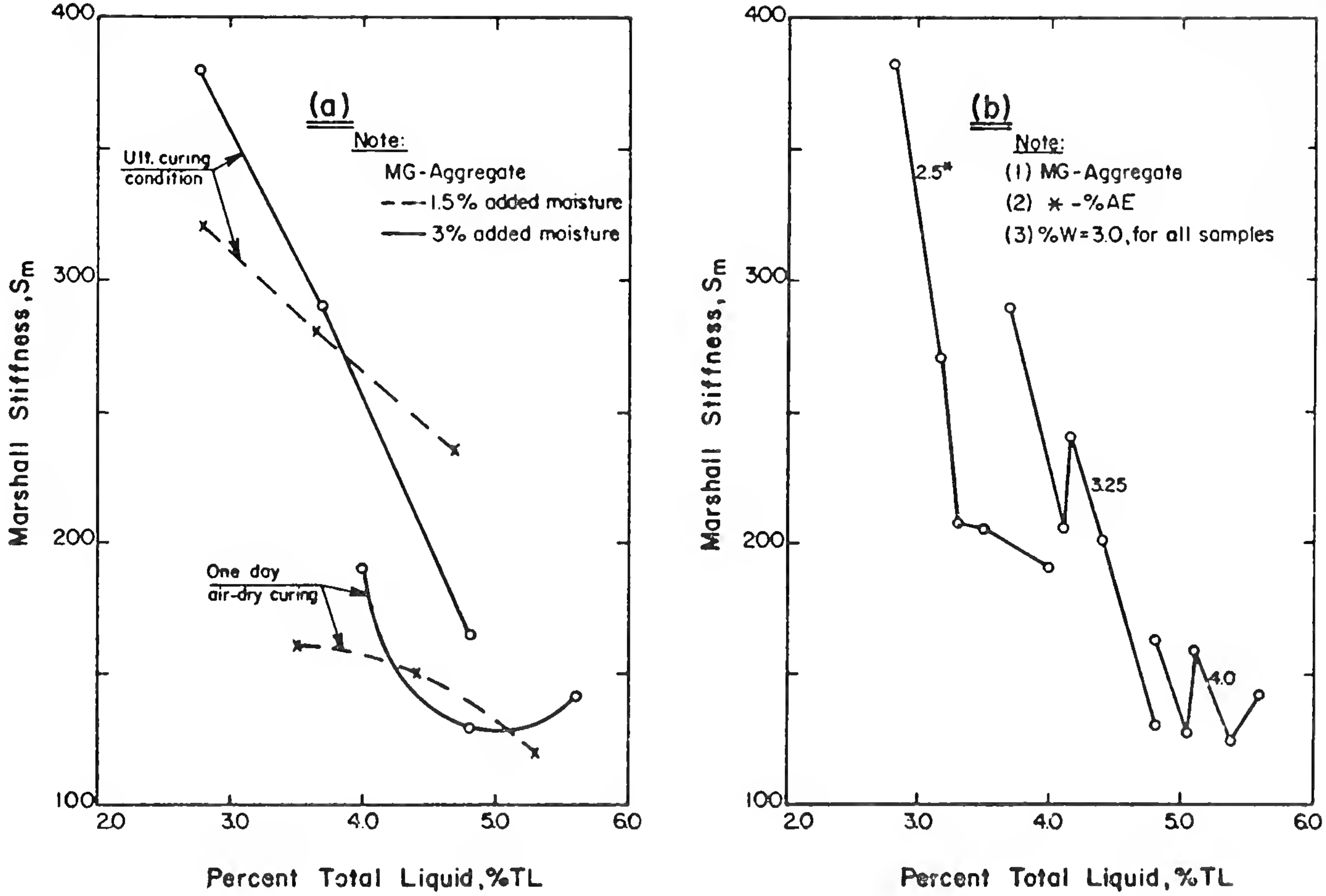


FIGURE 36, EFFECT OF PERCENT TOTAL LIQUID ON THE MARSHALL STIFFNESS FOR AETM (MG aggregate), (a) CHANGE IN %TL DUE TO CHANGE IN %AE USED, (b) CHANGE IN %TL DUE TO CHANGE IN CURING TIME (%W=3.0)

for samples with high AE do not increase appreciably. In contrast, by decreasing the %AE in the mix the gain in S_m increases significantly with time.

For any curing condition, the mix properties at a certain %TL depends mainly on the percent added moisture (Figure 36(a)), and the percent of asphalt emulsion residue (Figure 36(a), and (b)). In addition, the curing time is an important factor in controlling the S_m-%TL trends.

Water Sensitivity Test Results

The main purpose of these tests were to study the trend of AETM response to water damage at different curing periods. The tests were conducted on AETM specimens that contained 3% added moisture with varying percentages of asphalt emulsion residue at three different curing periods (see Table 7). The samples were cured for one and three days in the air-dry condition as well as the ultimate curing condition (3 days at 120°F) before conducting the water sensitivity tests.

Percent Moisture Absorption (%MA)

The percent moisture absorption decreased with an increase in the asphalt emulsion content in the sample (Figure 37). It should be noticed that the percent moisture absorption was higher for three days cured specimens than those of the one day cured specimens. This is mainly due to the change in air voids. Three days cured specimens possessed relatively higher air voids than the one day cured specimens which resulted from evaporation of part of the moisture portion in the mix. However, at the ultimate curing condition less moisture was absorbed in the samples as compared to the air dry condition. This resulted from the difference in behavior and characteristics of the AETM components, especially the asphalt emulsion, at these two different curing conditions (air dry vs. ultimate curing). In the case of air-dry samples there is relatively less adhesion, bond, and coating between the asphalt emulsion and the aggregate which provided a space for a portion of the moisture to be absorbed. Besides, the voids in this case are continuous in nature. On the other hand, in the ultimate curing condition the asphalt emulsion has

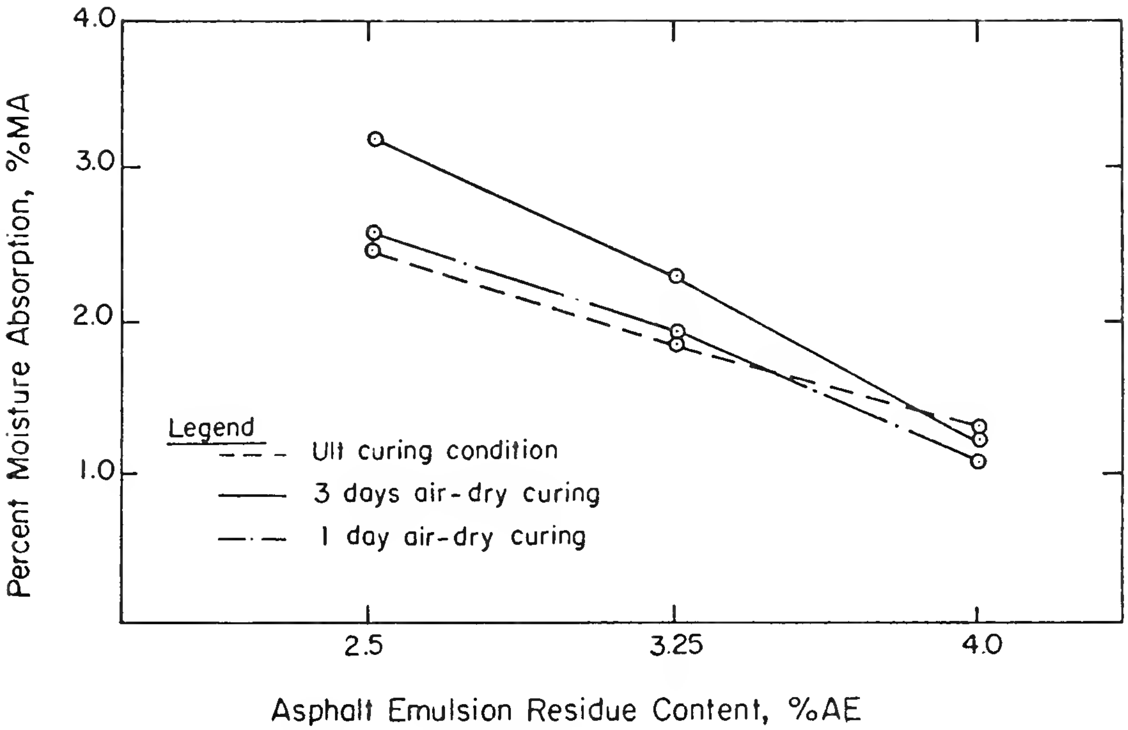


FIGURE 37, PERCENT MOISTURE ABSORPTION, (%MA) FOR DIFFERENT CURING PERIODS AND %AE (MG aggregate, 3% added moisture)

developed the properties of the asphalt residue (or approached it) and provided an intimate contact with the aggregate particles and reduced the amount of moisture absorped.

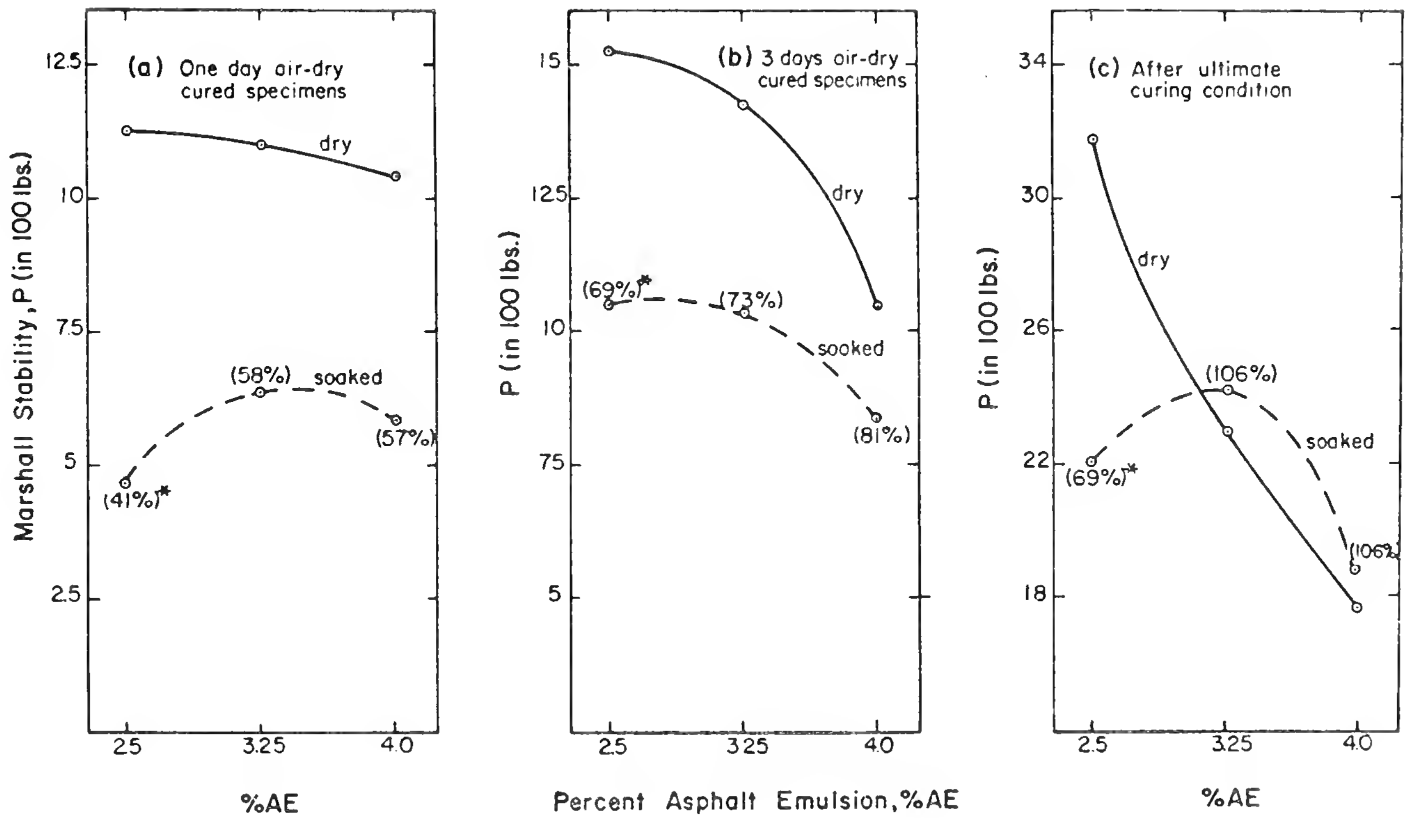
Percent Retained Stability

The Marshall stability values for dry and soaked conditions at the three curing periods are presented in Figure 38. A significant result of this test shows that at any curing level the percent retained stability increases with increasing asphalt emulsion content in the mix. Also, the "stability-asphalt emulsion content" relationships for the soaked samples follow a curvilinear pattern with an optimum %AE value that corresponds to a maximum stability value. In contrast, the dry test results followed a decreasing trend with increasing %AE. Longer curing periods for the dry specimens resulted in steeper stability trends (Figure 38). However, after subjecting the samples to the water sensitivity tests a significant drop in stability values occurred for samples with a low asphalt content.

A comparison between the dry and soaked stability values as a function of percent total liquid (%TL) is presented in Figure 39. For a specific curing time, the percent total liquid range for the soaked specimens represented relatively a smaller range for the different asphalt emulsion contents as compared to the %TL range for the dry samples. Samples with low %AE absorped more moisture during the water sensitivity test than those containing higher asphalt emulsion contents. In addition, the soaked specimen results followed a different trend than those of the dry specimens. This difference in the trends is more pronounced through the curing process of the dry specimens before the water sensitivity test.

Percent Retained Marshall Stiffness and Index Values

The percent retained Index and Stiffness values varied and depended mainly on the curing state of the dry specimens (Figures 40 and 41). It is apparent from the ultimate curing condition trends that the percent retained values for both Marshall Stiffness and Index increase with increasing asphalt emulsion percentages in the specimens.



Note:

MG - Aggregate
3% added moisture
* - Percent retained stability = $\frac{P_s}{P_d} \times 100$

FIGURE 38, MARSHAL STABILITY FOR DRY AND SOAKED SPECIMENS AFTER DIFFERENT CURING PERIODS

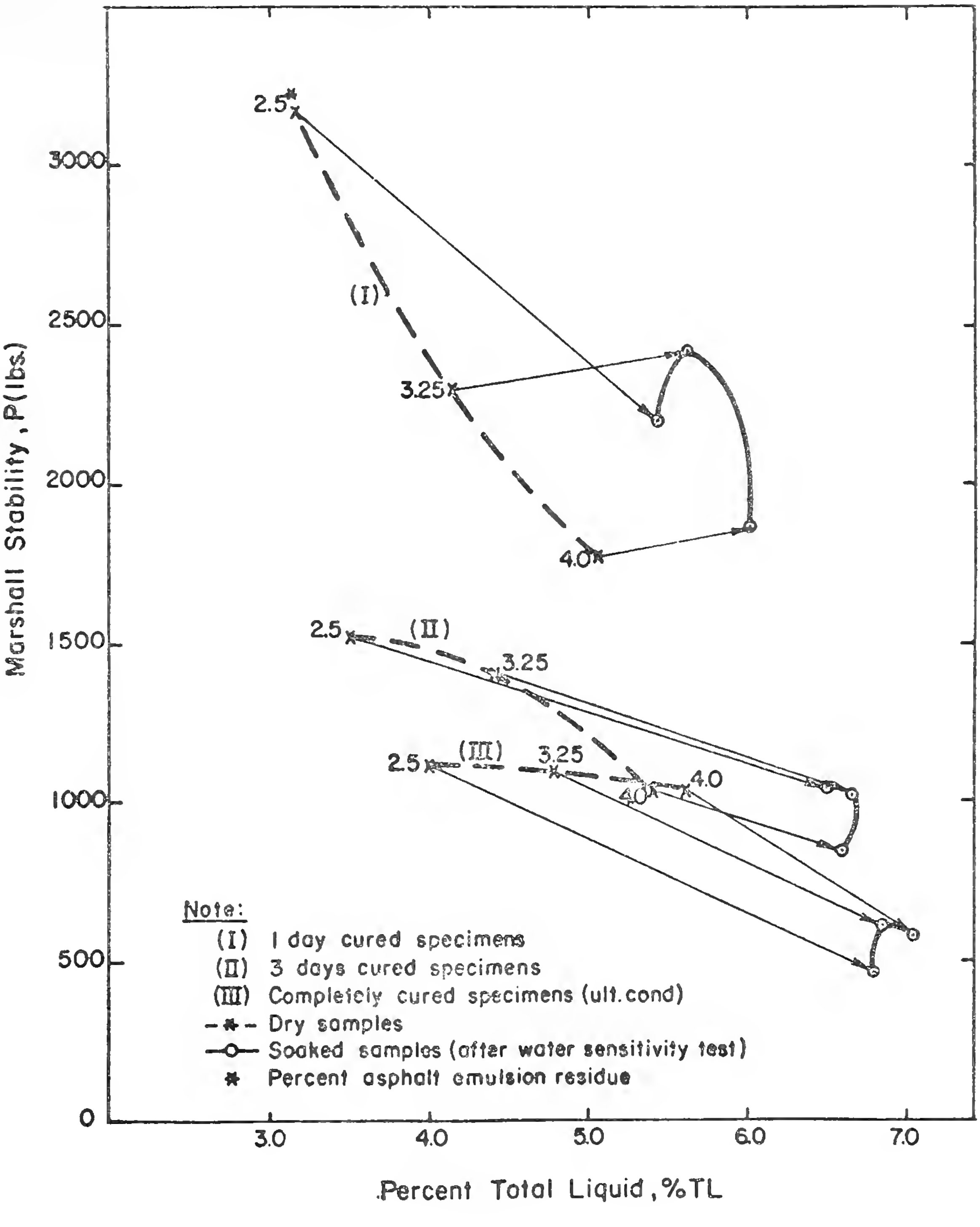


FIGURE 39, MARHALL STABILITY VALUES FOR DRY AND SOAKED SPECIMENS AS A FUNCTION OF PERCENT TOTAL LIQUID (MG aggregate, 3% added moisture)

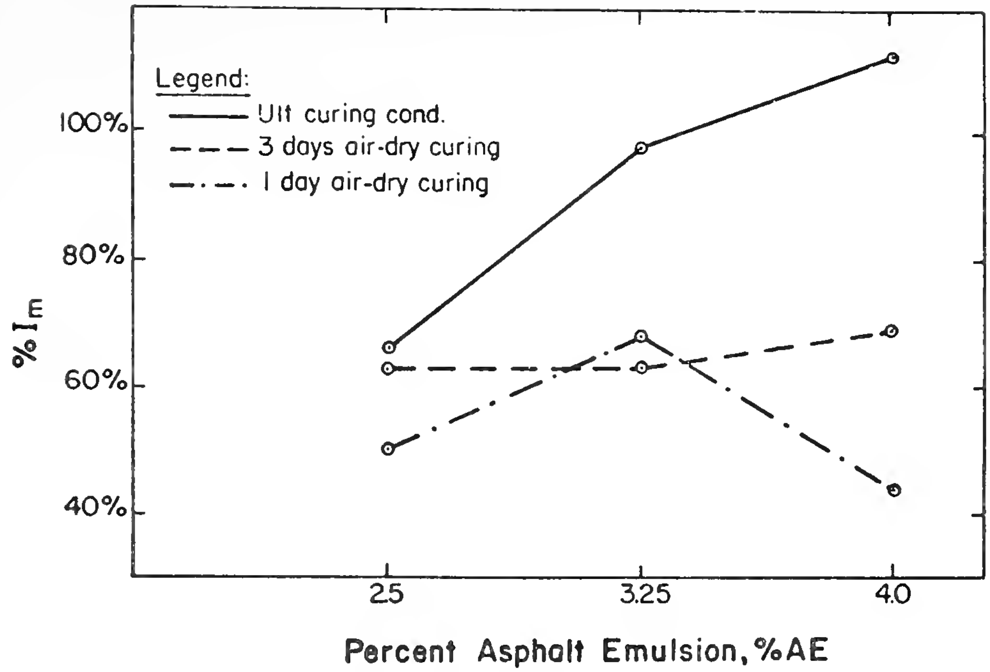


FIGURE 40, PERCENT RETAINED INDEX (% I_m) FOR AETM (MG aggregate, 3% added moisture)

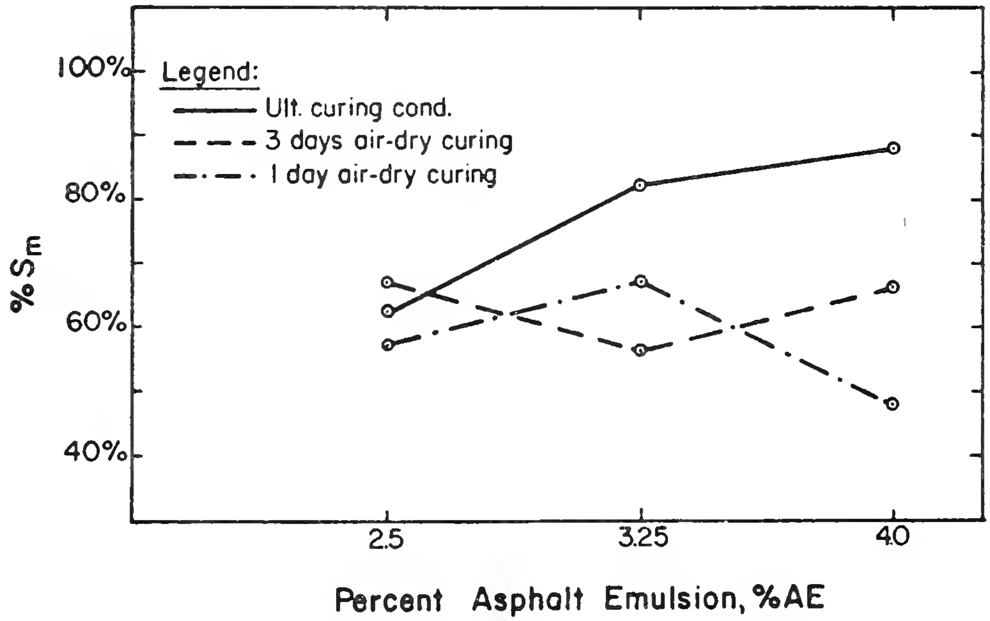


FIGURE 41, PERCENT RETAINED STIFFNESS (% S_m) FOR AETM (MG aggregate, 3% added moisture)

Summary of Results

The results summarized herein were obtained from the second phase of the evaluation study. The effect of curing time together with the asphalt emulsion and added moisture contents and their interaction on the properties of AETM were evaluated. All mixes in this phase of the study contained an MG aggregate. The following are the significant findings:

1. The percent of moisture retained is a function of the asphalt emulsion and added moisture contents and curing time. For a specific asphalt emulsion content, the difference in the percent of moisture retained due to using different initial added moisture decreases through the curing process. However, for the same initial added moisture the difference in $\%WC_0$, that resulted from using varying percents of asphalt emulsion, is about the same for the different curing periods.
2. The asphalt emulsion content significantly affects the stability of the mix and its effect is more pronounced through the curing process.
3. Air voids and total voids in the AETM are directly related to the curing time, %AE and %W. The two voids parameters increase while decreasing the %TL as a result of extending the curing period. Also, the higher the asphalt emulsion content the less voids will be available in the AETM.
4. The AETM stiffness indices S_m and I_m increase through the curing process. However, this gain in stiffness is dependent mainly on the asphalt emulsion content in the mix. Also, the added moisture content affects the trend of increase of the mix stiffness.
5. For a specified aggregate gradation, the higher asphalt emulsion content in the mix gave better resistance to water damage as measured by the water sensitivity tests. The effect of %AE is more pronounced through extending the curing time. The shape of the "stability vs. %AE" curve for soaked specimens is quite different from that obtained for the dry samples. This difference is more pronounced when the samples are allowed to cure for long periods of time.

It is the opinion of the author that high stability is generally obtained at the expense of lowered durability (measured here as the resistance to water damage) especially when using the dry Marshall stability trends in the design of AETM. The final design must provide a balance between stability and durability requirements. This would be achieved, when using "Marshall Method for the Design of AETM", by controlling and evaluating both the dry and soaked properties of the mix with a greater emphasis on the soaked specimen results. Due to the significant role of curing in influencing the AETM properties, it is believed that evaluating the AETM properties at two different curing states would be beneficial in providing an adequate understanding of the AETM properties and consequently allow a better control and design of the mix.

CHAPTER VIII: EFFECT OF AGGREGATE GRADATION ON AETM PROPERTIES

Introduction

The effect of aggregate gradation, asphalt emulsion residue, and added moisture contents on the properties of AETM were evaluated. Three aggregate gradations were used in the study. The gradations were selected within the ISHC gradation size #73B, and identified as FG, MG and CG (see Figure 4, for more detailed description of these gradations).

Two replications of the experiment (blocks) were used to provide more inference on the analysis and evaluation of the effect of aggregate gradation together with %AE and %W. Curing time at one day and seven days represented the two blocks (see Table 10). Using the two levels of curing provided the necessary information about the main effects:aggregate gradation, asphalt emulsion content, and added moisture content together with their interactions. In addition, all interaction effects with the curing factor were evaluated. However, no testing for the effect of curing time (one vs. seven days) was available in this part of the study. This was mainly due to the restriction on randomization caused by the blocking effect.

Table 10 presents the factorial design for this phase of the study. The two blocks are shown within the heavy lines for one and seven days curing. Three levels of aggregate gradation, three levels of asphalt emulsion content, and two levels of added moisture content were incorporated in the design. In addition to these two blocks, several mix combinations were tested at the three days curing and the ultimate curing condition, as shown in Table 10. The later mixes were not used in the analysis of variance. However, reference will be made to these test results whenever it is needed to provide a general trend for the curing effect and for the water sensitivity analysis.

The AETM properties were analyzed within the frame work of a fixed-effect randomized complete block design, RCBD (2). The curing time (1 and 7 days) corresponded to the blocks of RCBD.

TABLE 10, FACTORIAL DESIGN FOR STUDY OF THE EFFECT OF AGGREGATE GRADATION ON THE AETM PROPERTIES (phase 2; design 2)

Additives	Curing time +condition	%W \ Agg. Gradation / %AE (residual)	F.G.			M.G.			C.G.		
			2.5	3.25	4.0	2.5	3.25	4.0	2.5	3.25	4.0
(NO P.C.)	1 day	1.5%	X	X	X	X	X	X	X	X	X
		3%	X	X	X	X	X	X	X	X	X
	3	1.5									
		3	X	X	X	X	X	X	X	X	X
	5										
	7	1.5	X	X	X	X	X	X	X	X	X
		3	X	X	X	X	X	X	X	X	X
	ult. cond.	1.5									
		3	X	X	X	X	X	X	X	X	X

Note:

1- X dry test

2- O water sensitivity test

3- The ANOVA was conducted for mix combinations within the two blocks (1 and 7 days air-dry curing)

Analysis of Results

The following analysis of variance model was used to evaluate the AETM response variables:

$$Y_{ijklm} = \mu + C_i + \delta_{(i)} + G_j + A_k + W_l + CG_{ij} + CA_{ik} + CW_{il} + GA_{jk}$$
$$+ GW_{jl} + AW_{kl} + CGA_{ijk} + CGW_{ijl} + CAW_{ikl} + GAW_{jkl}$$
$$+ CGAW_{ijkl} + \varepsilon_{(ijkl)m}$$

where

Y_{ijklm} = measured or response variable

μ = overall true mean

C_i = true effect of curing time

$\delta_{(i)}$ = restriction error, random, NID (o, σ^2), completely confounded with the effect of the ith curing time

C_j = true effect of aggregate gradation

A_k = true effect of ashhalt emulsion content, %AE

W_l = true effect of added moisture content, %W

$\varepsilon_{(ijkl)m}$ = true random error, NID (o, σ^2)

The other terms denote the interactions among the main factors C, G, A, and W. All main factors are fixed. The subscripts assume the values:

i = 1, 2

j = 1, 2, 3

k = 1, 2, 3

l = 1, 2

m = 1, 2, 3

The original data for all the response variables were checked for homogeneity of variance prior to conducting the analysis of variance. The Foster-Burr Q-test results are summarized in Table 11. As a result, the analysis of variance was performed using the original data.

Table 12, presents a summary of the ANOVA results for AETM response variables. In addition a typical analysis of variance table is shown in Table B3 in the appendices.

TABLE 11. FOSTER-BURR TEST FOR HOMOGENEITY OF VARIANCE

Response Variable	Degree of Freedom	No. of Samples	$Q_{statistics}$	Homogeneity of Variance
γ_d	2	36	0.073	accept*
γ_w	2	36	0.075	accept*
$\%WC_o$	2	36	0.094	accept**
P	2	36	0.059	accept*
f	2	36	0.057	accept*
S_m	2	36	0.057	accept*
I_m	2	36	0.067	accept*

* $Q_{2,36,0.01} = 0.082$

** $Q_{2,36,0.001} = 0.100$

TABLE 12, SUMMARY OF ANOVA RESULTS FOR AETM PROPERTIES (phase 2; design 2)

Source of Variation \ Response Variables	γ_d	γ_w	P	F	S_m	I_m	$\%WC_o$
C	—	—	—	—	—	—	—
G	S	S	S	S	S	S	S
A	S	S	S	S	S	S	S
W	S	S	S	S	N.S.	N.S.	S
CG	S	S	N.S.	S	S	S	S
CA	S	S	S	S	S	S	S
CW	S	S	S	S	N.S.	N.S.	S
GA	S	S	S	N.S.	S	N.S.	S
GW	N.S.	N.S.	S	S	S	S	S
AW	S	S	S	N.S.	S	S	S
CGA	N.S.	S	N.S.	N.S.	S	N.S.	S
CGW	N.S.	N.S.	S	N.S.	S	N.S.	N.S.
CAW	N.S.	N.S.	S	N.S.	S	S	S
GAW	N.S.	S	N.S.	S	S	S	S
CGAW	N.S.	N.S.	S	S	S	N.S.	S

NOTE:

1 – S = Significant at $\alpha = 0.05$
2 – N.S. = Not significant at $\alpha = 0.05$
3 – —— = No test available

The following sections present the evaluation of each one of the AETM response variables.

Percent Moisture Retained in the Sample, $\%WC_o$

The percent moisture retained in the AETM samples was significantly affected by all factors and their interactions except that of the interaction between curing, gradation, and added moisture content which was not significant.

Figure 42 shows the percent moisture retained at time of testing, for the one day and seven days cured specimens, as a function of aggregate gradation, %AE, and %W. The percent moisture retained ($\%WC_o$) ranged between 0.5 and 1.6 percent (by weight of the dry aggregate). At seven days curing, the difference in $\%WC_o$ due to varying aggregate gradation, %AE, or %W was relatively less than that observed for one day cured specimens. In addition, for one day cured specimens (Figure 42(a)) the effect of aggregate gradation and percent added moisture on the $\%WC_o$ values was more pronounced at the low asphalt content. This effect was reduced with increasing asphalt content.

For seven day cured specimens (Figure 42(b)) the $\%WC_o$ range was small for FG and MG aggregate mixes at the different %AE and %W. However, there was relatively large variation in $\%WC_o$ for CG aggregate mixes.

In viewof the presented results, it can be concluded that at early curing conditions (e.g. one day) the effect of aggregate gradation and added moisture content on $\%WC_o$ is dependent on the asphalt content in the mix. The higher the %AE, the less the variation in $\%WC_o$ that results from changing aggregate gradation and/or added moisture content. However, after relatively longer periods of curing (e.g. 7 days) the interaction effect of the aggregate gradation with the %W is not significantly apparent.

Dry and Wet Unit Weights (γ_d and γ_w)

The main factors (aggregate gradation, %AE and %W) significantly affected the dry and wet unit weights of the AETM specimens. In addition,

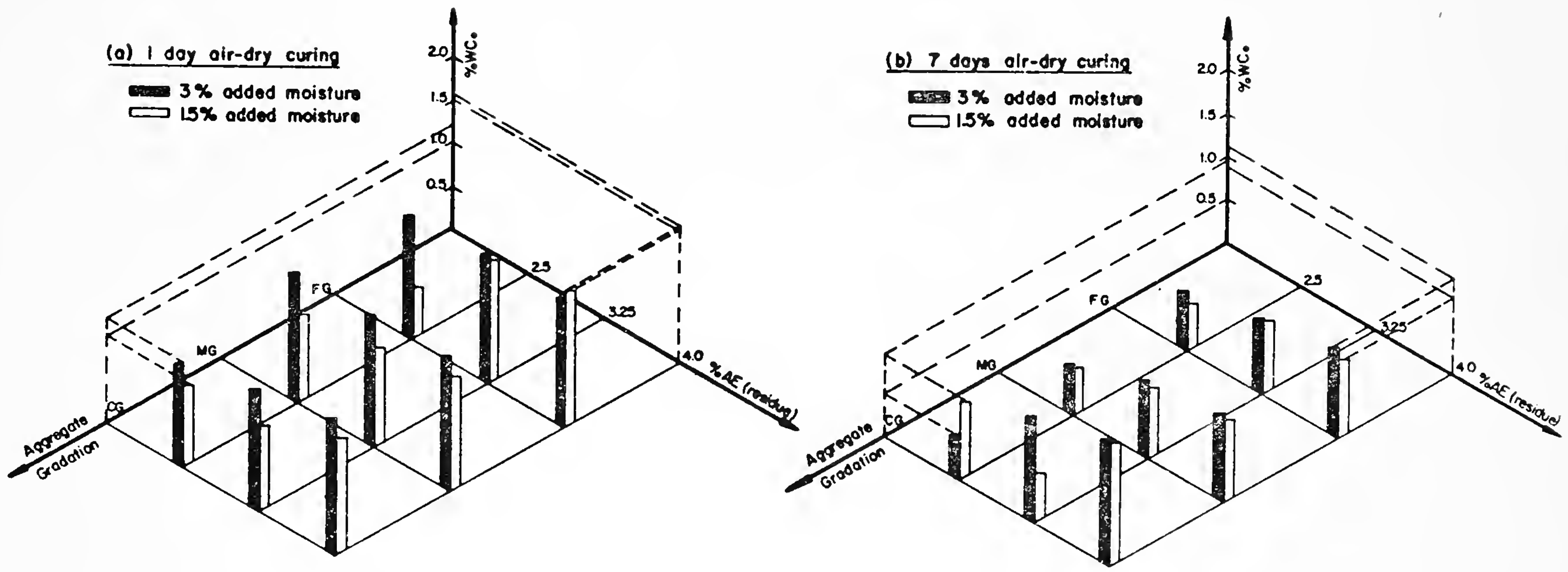


FIGURE 42, EFFECT OF INTERACTION AMONG AGGREGATE GRADATION, PERCENT ASPHALT EMULSION (%AE), PERCENT ADDED MOISTURE (%W) ON PERCENT MOISTURE RETAINED (%WCo) FOR TWO CURING PERIODS

the aggregate gradation and %AE had a greater effect on the dry and wet unit weights as compared to the added moisture content, %W, (this is based on the mean square value that is attributed to each factor in the analysis of variance). Also, all two-factor interactions were significant except the interaction between aggregate gradation and added moisture content which was not significant. The most significant two-factor interaction was the interaction between curing time and added moisture content.

The relationship between dry unit weight (γ_d) and aggregate gradation, %AE, and %W for the two curing periods is shown in Figure 43. It is apparent that the higher the asphalt content in the mix the higher the γ_d values. Besides, the CG gradation samples resulted in higher dry unit weights than the MG gradation samples. The FG gradation samples resulted in the least dry unit weights. This is more appreciated when studying Figure 44, which presents the test results for the different curing periods (note that all test results presented in this figure are for samples with 3% added moisture).

For a specific %AE, %W and aggregate gradation the dry unit weights of the samples are about the same throughout the curing process (Figure 44).

Marshall Stability, P

Marshall stability values (P) were significantly affected by all the main factors together with most of the two-factor and three-factor interactions (see Table 12). The aggregate gradation showed the most significant effect on the stability values as compared to the asphalt emulsion and added moisture effects. Figure 45 presents the stability values as related to aggregate gradation, asphalt emulsion content, and added moisture content for the two curing periods. Presenting the data in this form aids in providing a better understanding of the effect of the main factors together with their interactions.

For specimens cured one day and seven days, FG gradation provided the highest stability at all levels of %AE and %W. The lowest stability values were obtained for mixes with CG gradation. The MG gradation mixes

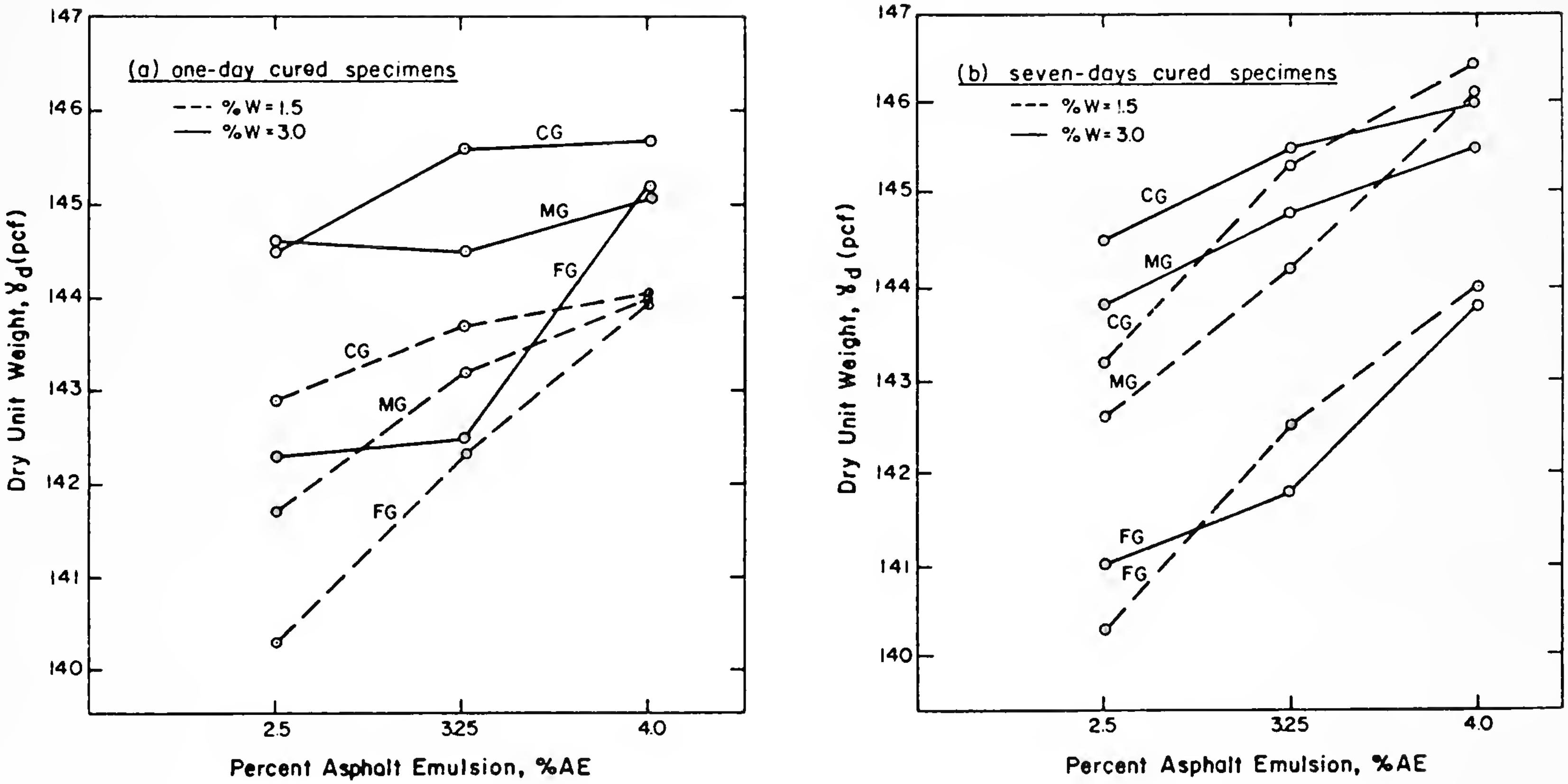


FIGURE 43, EFFECT OF AGGREGATE GRADATION, ASPHALT EMULSION CONTENT, AND ADDED MOISTURE CONTENT ON THE DRY UNIT WEIGHT (γ_d) OF THE AETM SPECIMENS AT TWO CURING PERIODS.

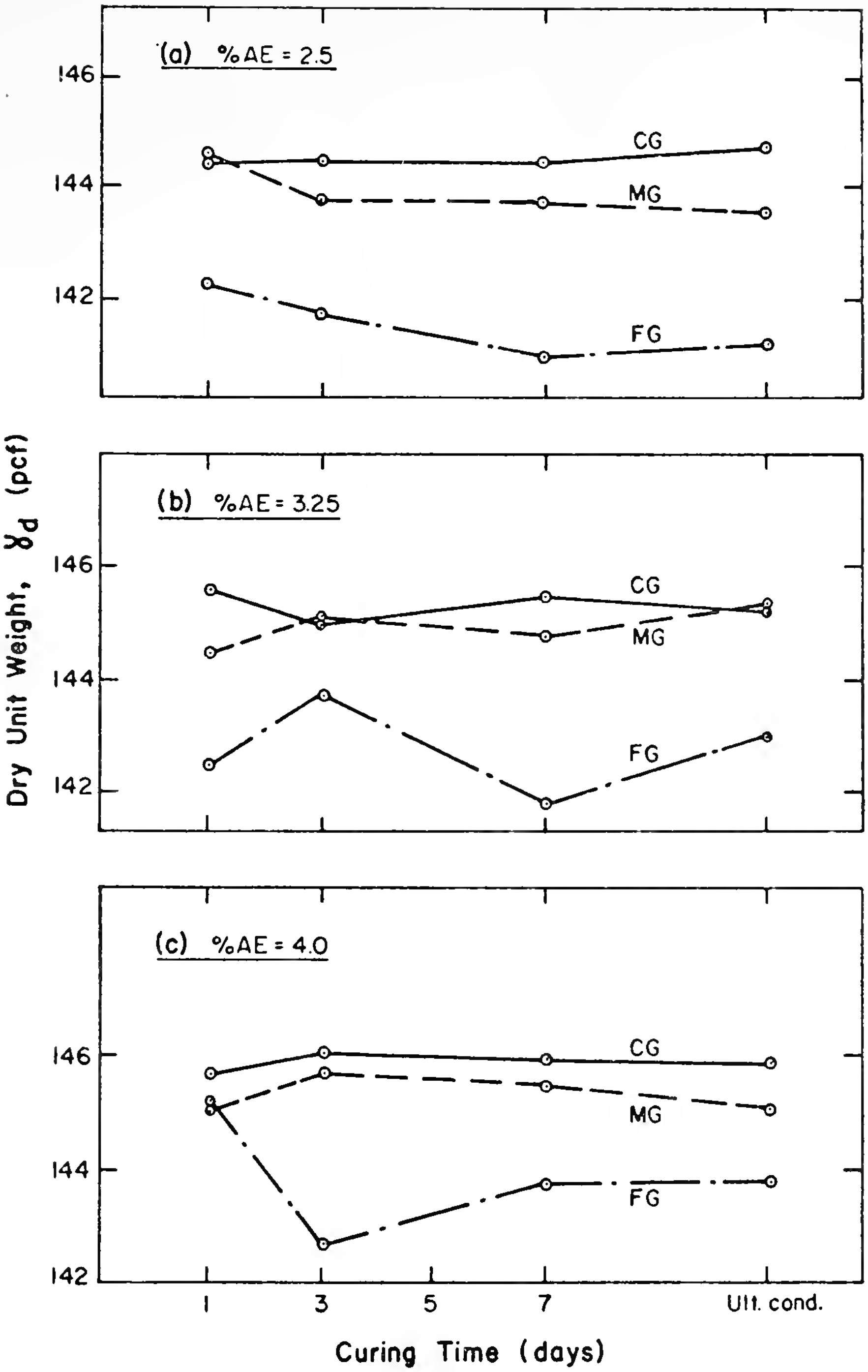


FIGURE 44, INFLUENCE OF AGGREGATE GRADATION ON γ_d AS A FUNCTION OF CURING TIME FOR DIFFERENT %AE (3% added moisture)

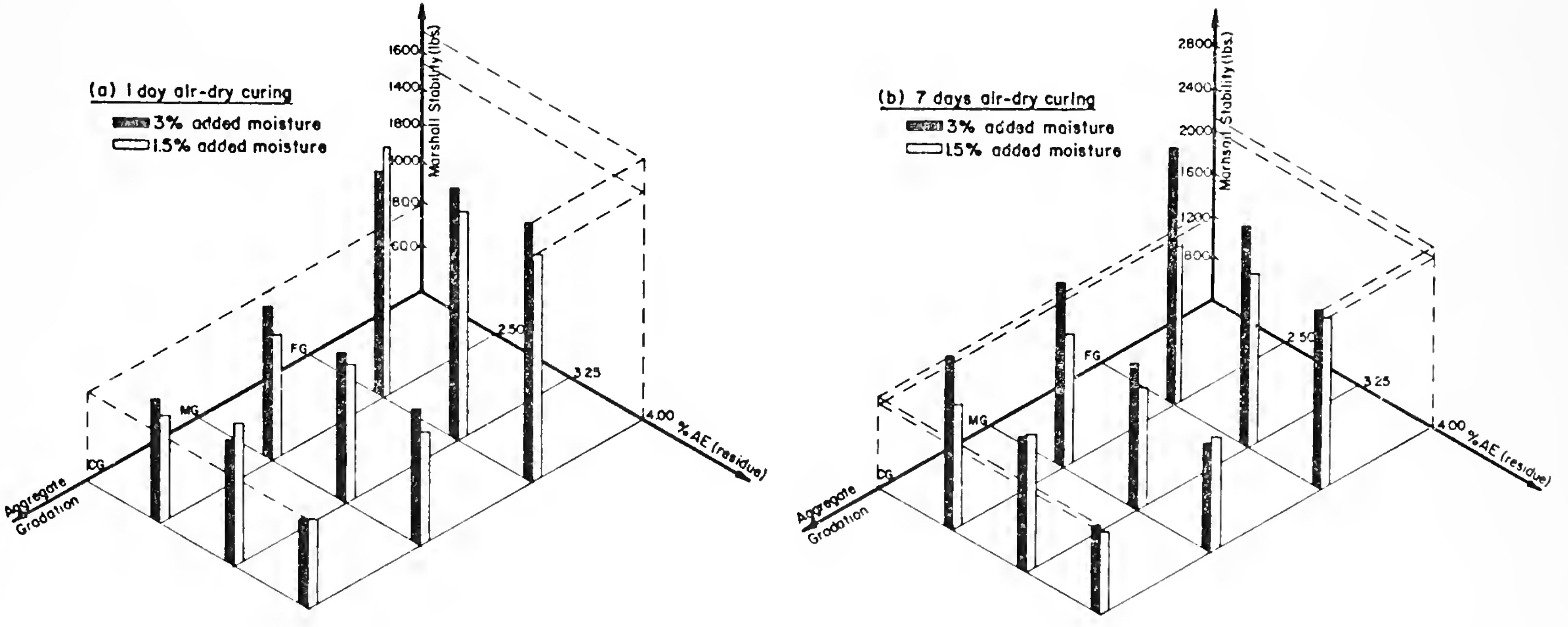


FIGURE 45, EFFECT OF AGGREGATE GRADATION, PERCENT ASPHALT EMULSION RESIDUE, AND PERCENT ADDED MOISTURE ON MARSHALL STABILITY

resulted in a higher stability than those of the CG gradation mixes. It should be noted that the difference between the FG and MG grain size distribution was twice the difference between MG and CG grain size distribution (see Figure 4). This affected the characteristics of the stability results. The MG mixes provided Marshall stabilities that were closer to the CG mixes than those of the FG mixes.

The effect of %AE for one day cured specimens is apparent but not to the same degree and significance as for the seven day cured specimens. Besides, the AETM with FG and MG gradations produced, in general, higher stability values for mixes with 3%W than with 1.5% added moisture (%W), however, the effect of added moisture content for CG mixes was very small or reversed when compared to the remaining two gradations. This is due to the nature of the gradations, FG and MG gradations posses more surface area than the CG gradation. Thus, they require relatively larger amounts of liquid to provide adequate coating and strength. This is more apparent when one considers the seven day curing results, which show that if the samples were evaluated after one day curing the effect of the added moisture on the strength of AETM (P in this case) could have been under-estimated. Evaluating the AETM properties after relatively long periods of curing would provide more understanding of the role of each of the liquid components on the mix, especially the added moisture content.

The increase or gain in stability values through the curing process for the different aggregate gradations is shown in Figure 46. The more the aggregate gradation shifts toward the fine limit of the gradation band, the steeper will be the curing trend and consequently the more rapidly the AETM will develop its strength (represented here as the Marshall Stability). This could be appreciated by comparing the stability trends for the different gradations at any specific %AE (Figure 46). Also, for a specific %AE at any curing period the FG aggregate resulted in the highest stability values followed by the MG and then CG specimens.

Another way of evaluating the effect of aggregate gradation is by studying the "stability - %TL" trends (Figure 47). The change in percent total liquid, at time of testing, supports the previous discussion and shows the significant effect of aggregate gradation in the stability trends.

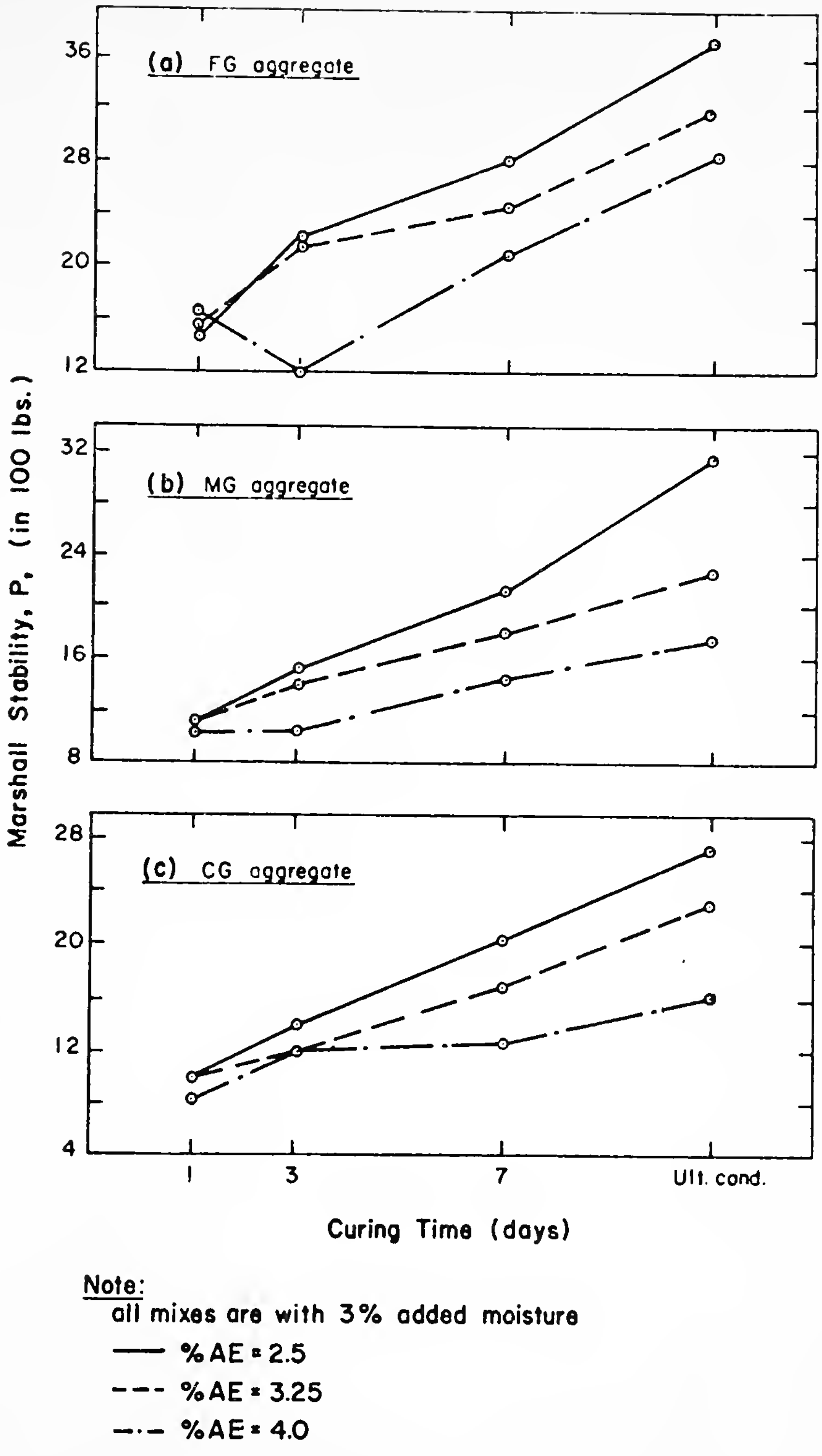
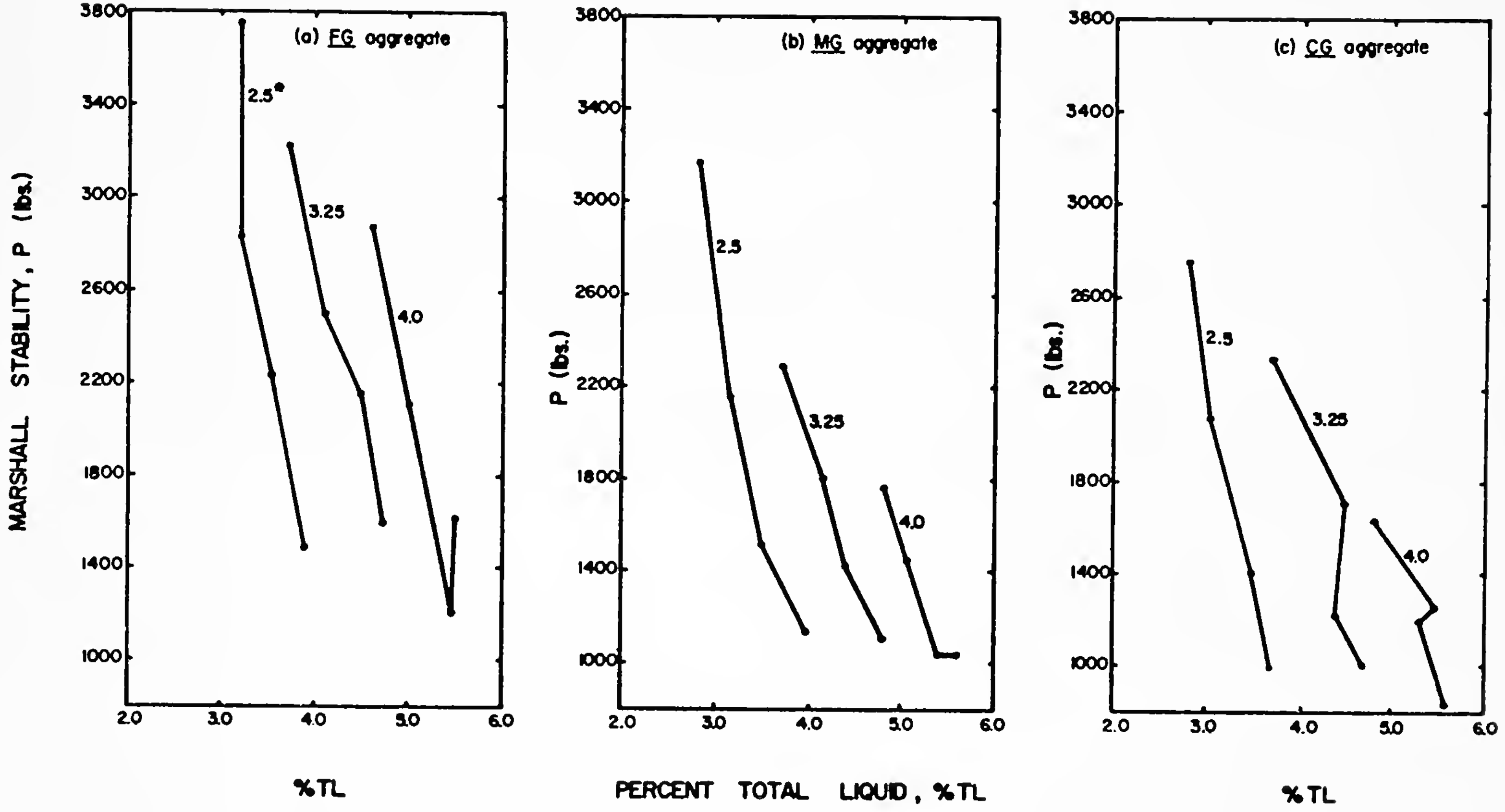


FIGURE 46, INFLUENCE OF AGGREGATE GRADATION AND %AE ON MARSHAL STABILITY (P) AS A FUNCTION OF CURING TIME



NOTE: 1-test data are for 3% initial added moisture.
2-*values shown on graphs indicate %AE residue used.

FIGURE 47, RELATIONSHIP BETWEEN MARSHALL STABILITY (P) AND PERCENT TOTAL LIQUID (%TL) FOR DIFFERENT AGGREGATE GRADATIONS AND %AE.

Marshall Flow, F

The Marshall Flow (F) values ranged between 6 and 8.5 for all mix combinations after one day curing. The F range for seven day cured specimens was from 6.0 to 11.5. In general the curing time and its interaction with the added moisture content had the most significant effect on the flow values.

The flow values are presented in Figure 48. Larger amounts of asphalt emulsion resulted in higher flow values. Increasing F values occurred as a result of extending the curing time before testing the specimens. This is a direct result of the fact that through the curing process the mix loses a portion of the available moisture which in turn makes the role of the emulsion residue in the mix more apparent in terms of increase in flow values.

Also, the gradation of the aggregate significantly affected the flow values. The FG aggregate provided the mix with relatively lower flow characteristics which was more apparent in mixes with low asphalt emulsion content. In addition, the roles of %W and aggregate gradation were more pronounced after relatively longer curing periods (see Figure 48(b)).

Air Voids and Total Voids

Figure 49 depicts the percent air voids ($\%V_A$), as related to aggregate gradation, %AE, and %W for the two curing periods. The aggregate gradation was a main factor in affecting the air voids in the mix. FG gradation provided mixes with higher $\%V_A$ than the MG or CG mixes at the two curing periods. Also, for one day cured specimens, the percent added moisture affected $\%V_A$. However, at seven days curing the difference in $\%V_A$ due to changing the added moisture content was reduced.

The percent air voids in the mix are directly related to %AE. At low %AE, the air voids are higher than for mixes with high %AE. Also, the effect of %W is more apparent at low %AE and decreases with the increase in %AE. Again this effect was reduced through the curing process.

Figure 50 presents the test data for percent air voids at different curing periods for the three different aggregate gradations. MG and CG gradations are closer to the theoretical maximum density gradation which

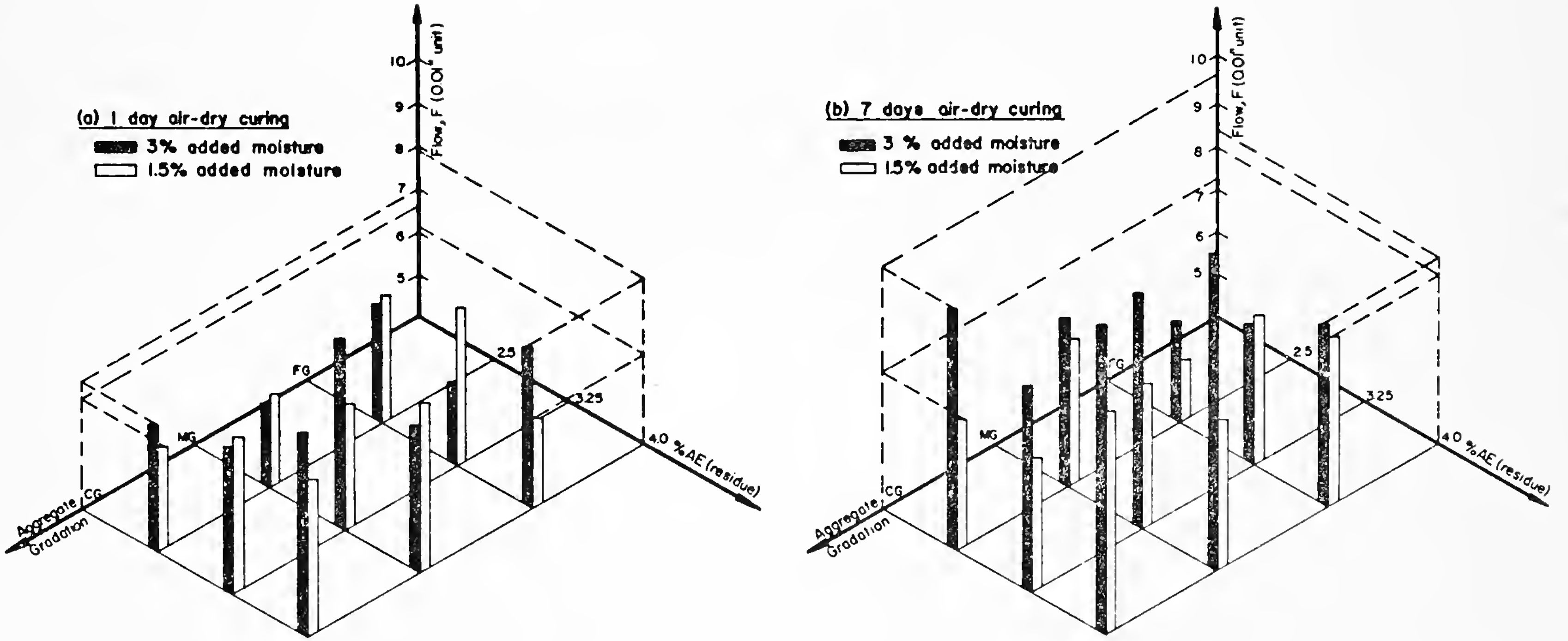


FIGURE 48, EFFECT OF INTERACTION AMONG AGGREGATE GRADATION, PERCENT ASPHALT EMULSION (%AE), PERCENT ADDED MOISTURE (%W) ON MARSHALL FLOW VALUES (F) FOR TWO CURING PERIODS

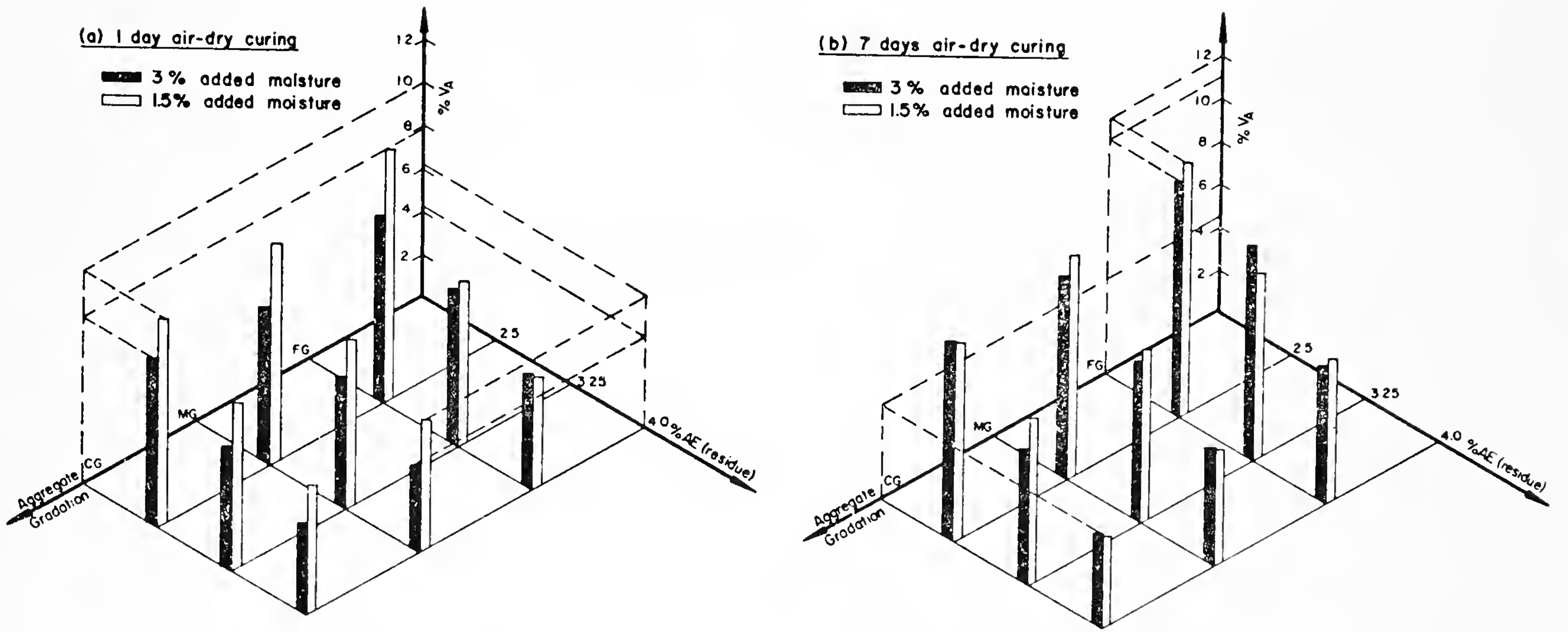


FIGURE 49, EFFECT OF AGGREGATE GRADATION, PERCENT ASPHALT EMULSION, AND PERCENT ADDED MOISTURE ON PERCENT AIR VOIDS ($\% V_A$)

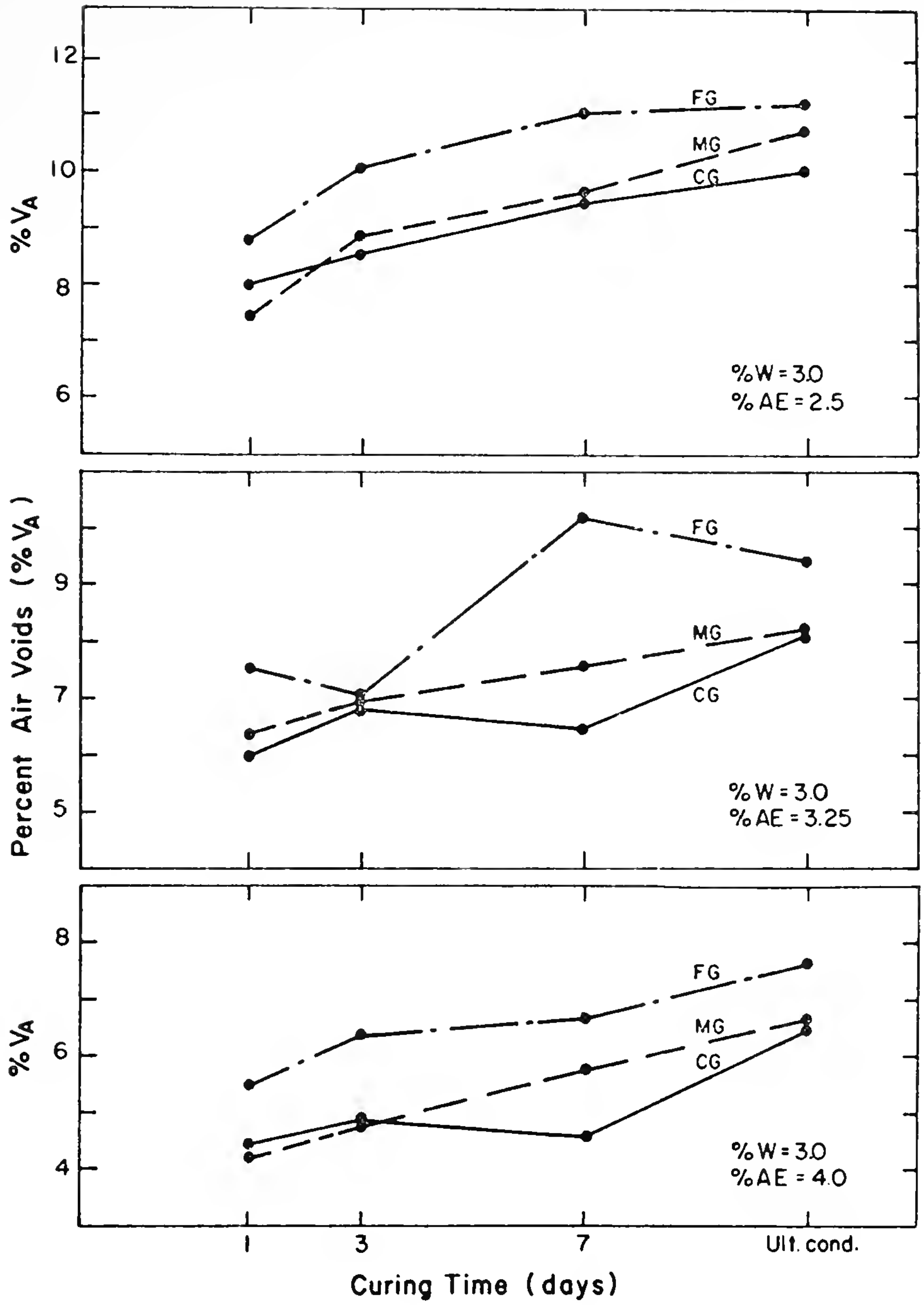


FIGURE 50, INFLUENCE OF AGGREGATE GRADATION ON PERCENT AIR VOIDS AS A FUNCTION OF CURING TIME

provided an adequate range of particle sizes and resulted in relatively higher densities and less $\%V_A$ in the mix as compared to the FG mixes (see Figure 49 and 50). This raises an important point which could be noticed throughout this phase of the study; the three gradations significantly affected the properties of AETM even though they fell within a specific aggregate gradation band. Greater care has to be taken in controlling the aggregate gradations in the mix.

Figure 51 presents the percent total voids ($\%V_T$) in the mix for the different aggregate gradations. FG aggregate mixes contained the highest $\%V_T$. The percent total voids in the mix for a specific %AE, %W and aggregate gradation was about the same at the different curing periods. The $\%V_T$ measured for samples after relatively a short curing time provides a good estimate for the $\%V_T$ at any stage of curing. The total voids parameter ($\%V_T$), consists of two components; percent air voids ($\%V_A$) and percent of voids filled with moisture ($\%V_w$). An increase in $\%V_A$ through the curing process has to be accompanied with a decrease in $\%V_w$ of about the same magnitude. Whereas, the $\%V_A$ will change with curing time depending on the mix components (aggregate gradation, %AE, and %W) as discussed earlier in this section.

Marshall Stiffness (S_m) and Index (I_m)

Aggregate gradation was the most significant factor that affected both I_m and S_m. The more the aggregate gradation shifts toward the fine limit of the gradation band, the higher will be the resulting stiffness parameters (I_m and S_m). Also, curing time and %AE significantly affected these two parameters. However, as indicated in earlier parts of the study, the added moisture content was not significant in its effect. The interaction effect of %AE and %W is of importance in influencing the I_m and S_m values. However, this effect depends also on the curing factor (especially in case of I_m).

It is of importance to note the interaction effect between aggregate gradation, %AE, and %W at the two curing periods (Figure 52). I_m and S_m values for FG aggregate mixes were higher for samples with high percent added moisture, however, by increasing %AE to 4% the trend is reversed.

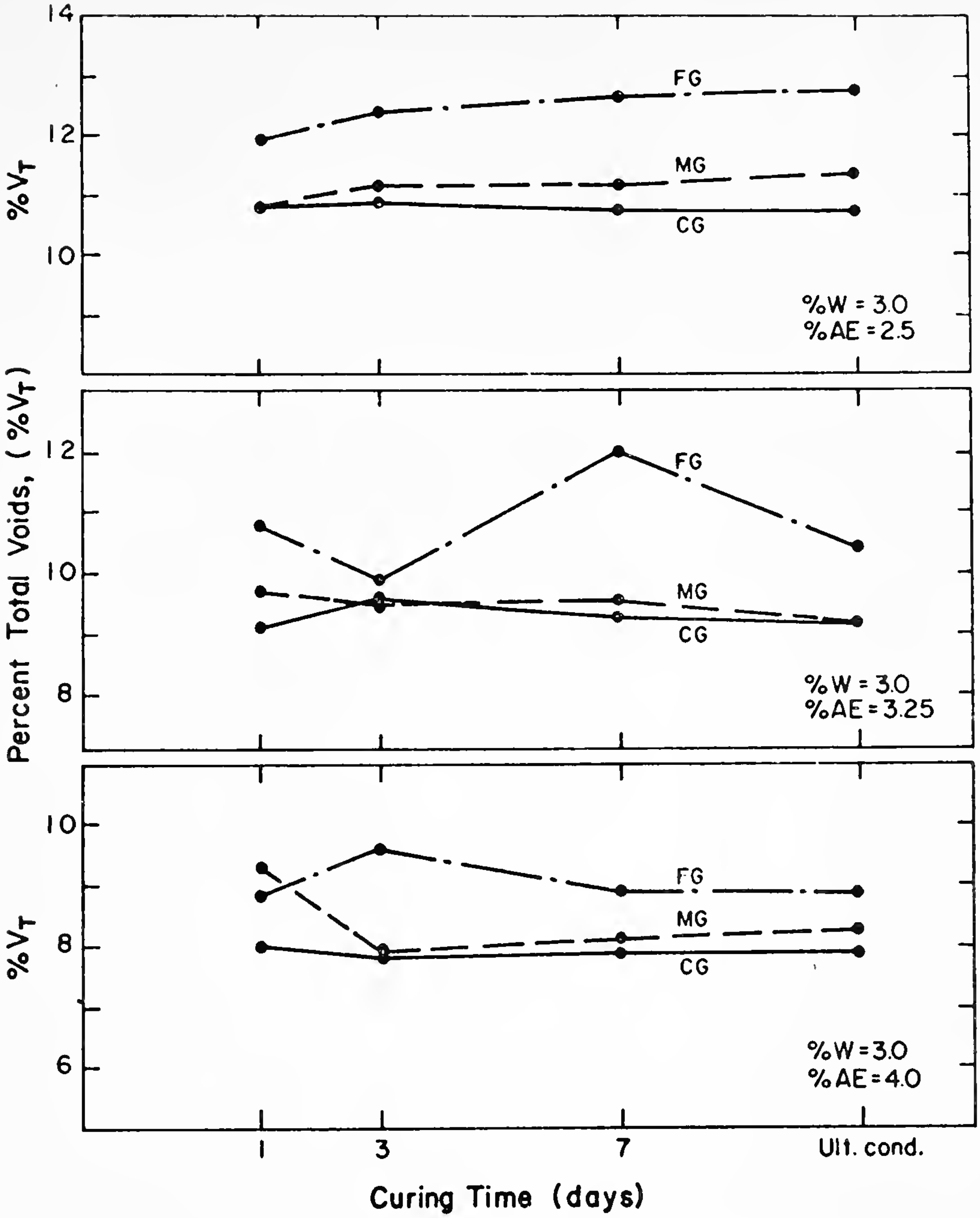


FIGURE 51, INFLUENCE OF AGGREGATE GRADATION ON PERCENT TOTAL VOIDS AS A FUNCTION OF CURING TIME

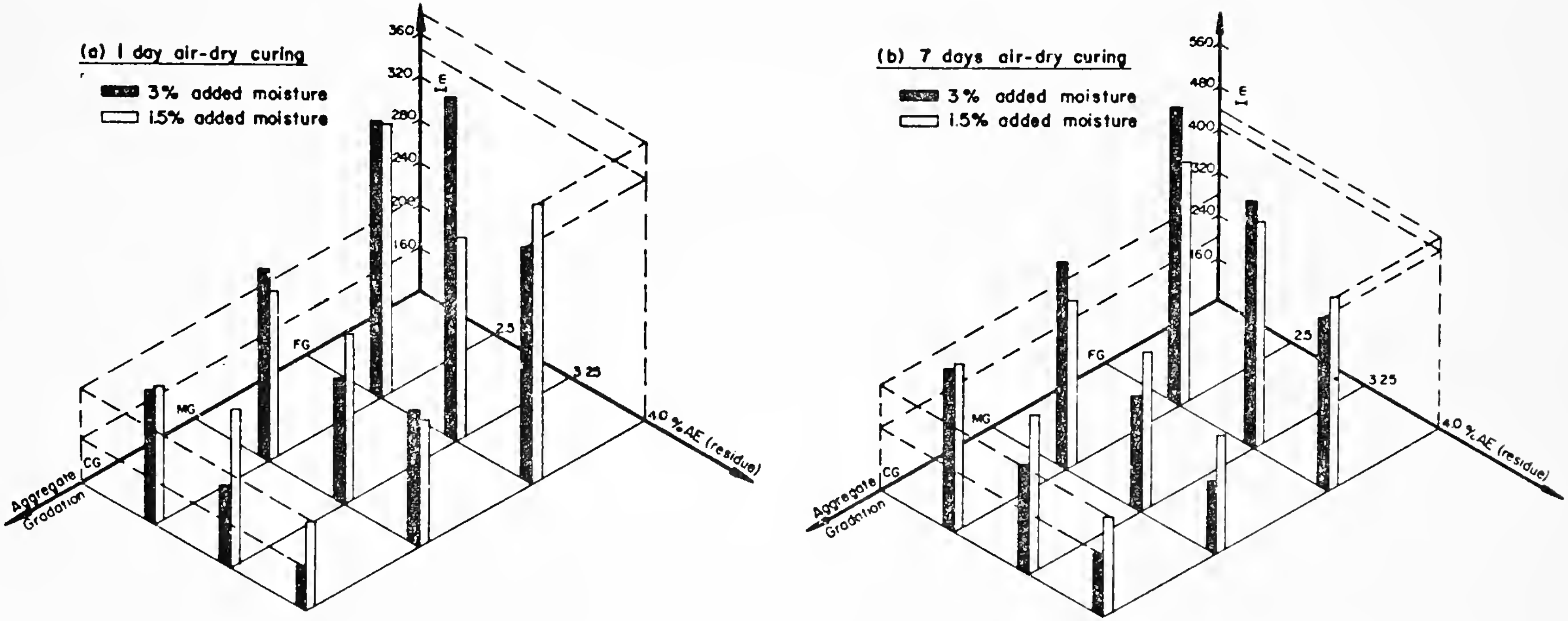


FIGURE 52, EFFECT OF AGGREGATE GRADATION, PERCENT ASPHALT EMULSION, AND PERCENT ADDED MOISTURE ON MARSHALL INDEX (I_m)

It should be noted that the difference was reduced through the curing process (1 vs. 7 days). For the MG gradation the trene depends on %AE residue. When using FG mixes, the relatively low added moisture content (1.5%) provided the mix with higher I_m and S_m at the two curing periods, as compared to using 3% added moisture. In general, with FG mixes the higher the amount of initial moisture used the higher will be the measured strength parameters. However, for CG mixes the low initial added moisture contents resulted in higher strength parameter as opposed to using high initial added moisture content.

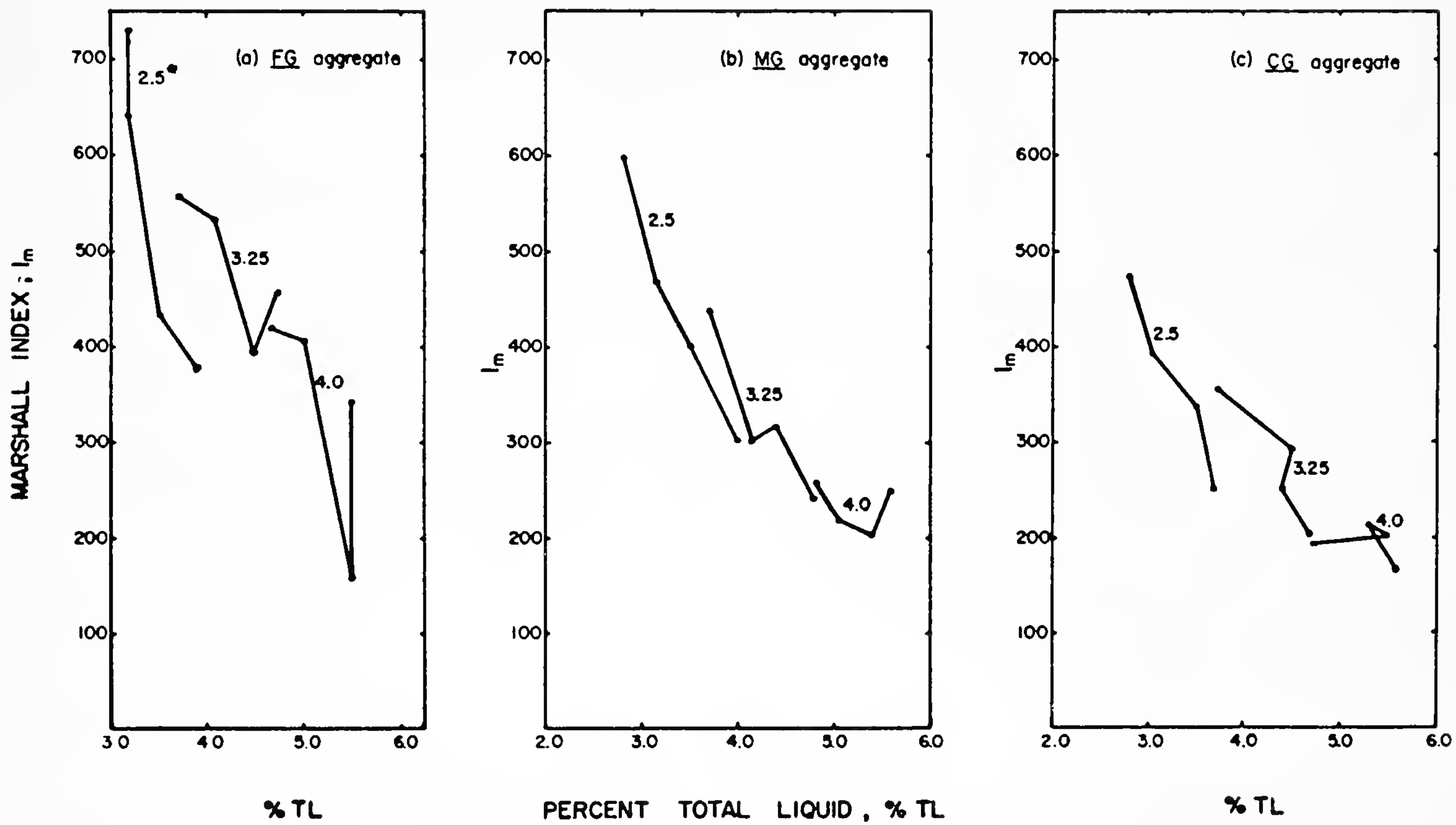
Figures 53 and 54 present the I_m and S_m results as a function of %TL, respectively. The data are for samples with 3% added moisture. The change in %TL was obtained through the curing process. The I_m and S_m results poses, in general, the same trends, with the I_m values haveing relatively higher values. It is of interest to note the significant effect of the aggregate gradation in controlling the position of the "I_m-%TL" relationship in the I_m scale (same is true for S_m). Also, the interaction between the aggregate gradation and the asphalt emulsion content is more pronounced in these two graphs.

Water Sensitivity Test Results

AETM containing 3.25% asphalt emulsion residue content and 3% added moisture content were used for the water sensitivity tests. The comparison study was conducted for the three different aggregate gradations at three different curing periods; one and three days air-dry curing and the ultimate curing conditions (see Table 10). Therefore, it has to be understood that the discussion in this part pertains to a specific asphalt emulsion and added moisture contents.

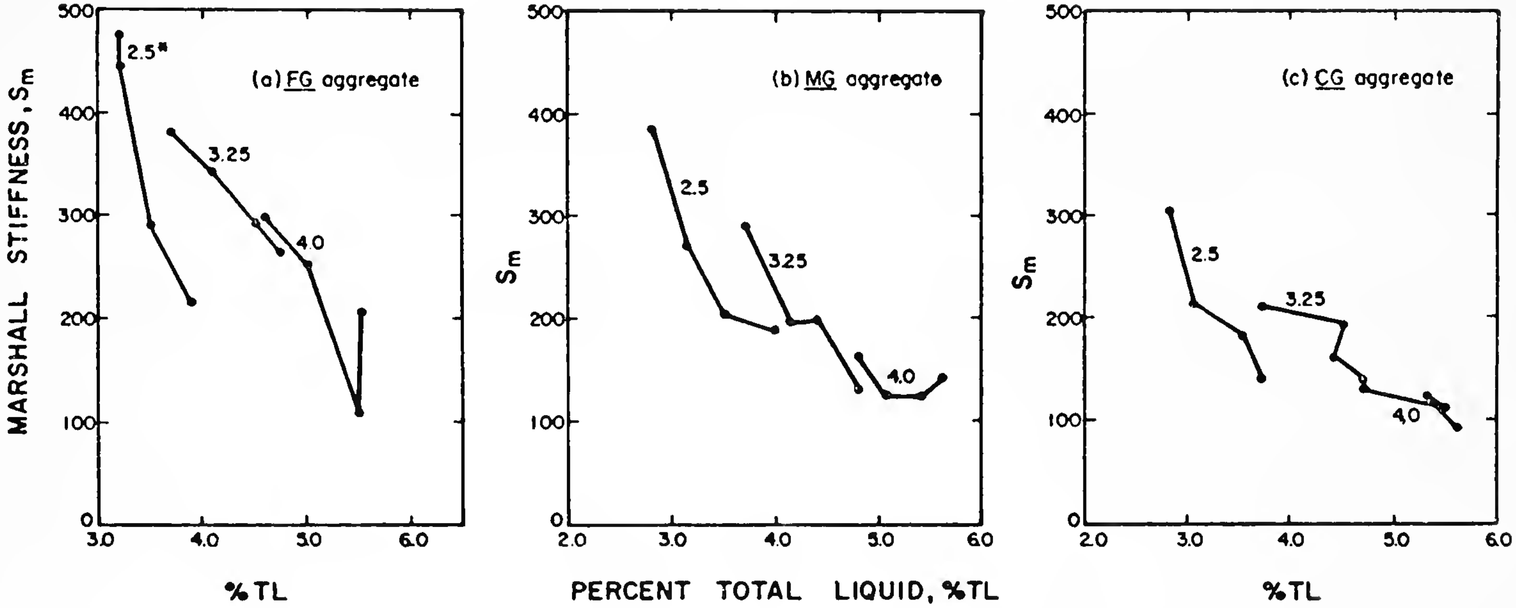
Percent Moisture Absorption (%MA)

At early curing periods (1 and 3 days air-dry curing), the percent moisture absorption (%MA) was higher for samples in FG mixes than those in MG or CG mixes (Figure 55). However, after the mixes were cured to the ultimate condition this relation was reversed. An increased amount of moisture absorption was obtained for the coarser gradations (given



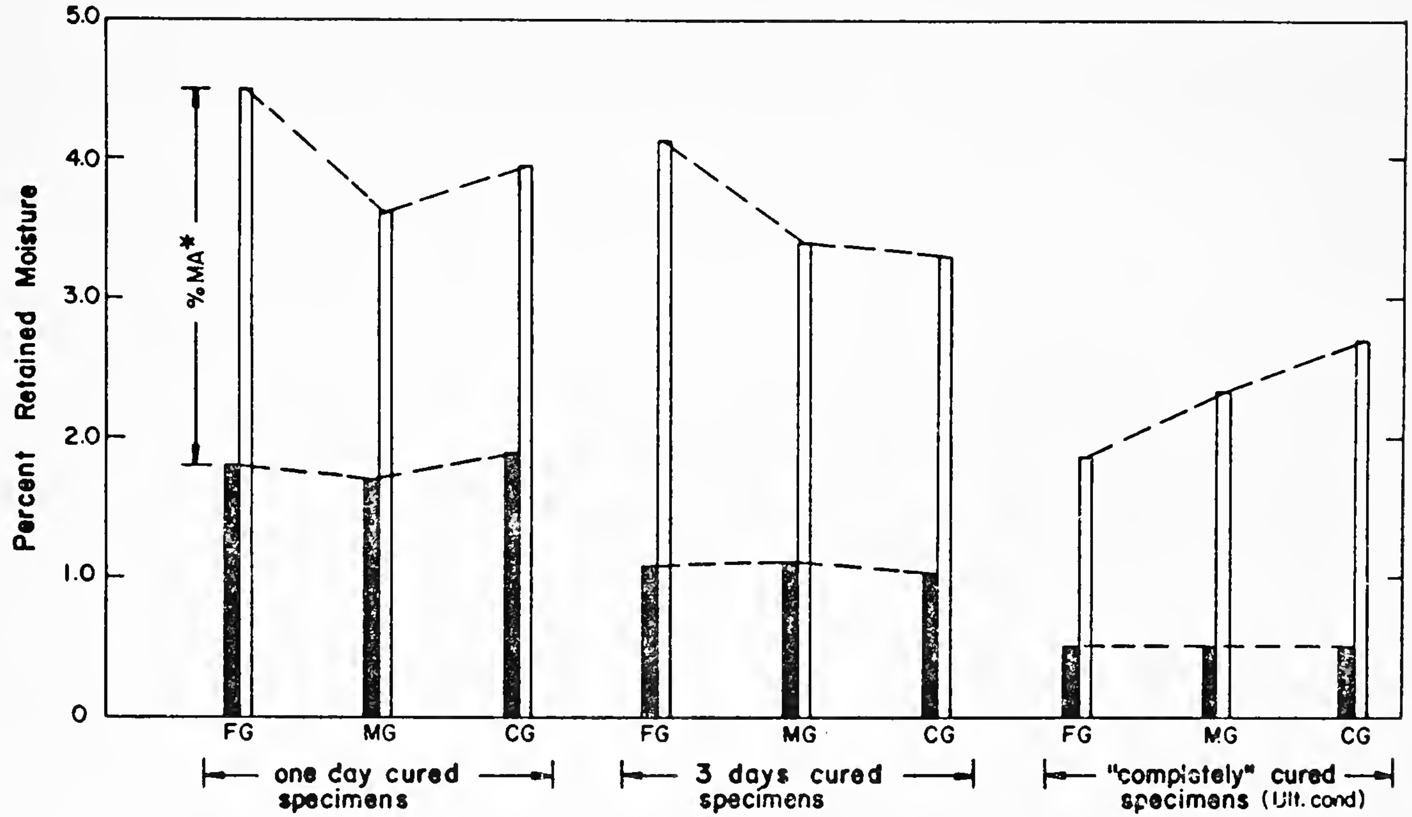
NOTE: 1-test data are for 3% initial added moisture.
2-* values shown on graphs indicate %AE residue used.

FIGURE 53, RELATIONSHIP BETWEEN MARSHALL INDEX , I_m , AND PERCENT TOTAL LIQUID, %TL , FOR DIFFERENT AGGREGATE GRADATIONS AND %AE



NOTE: 1- test data are for 3% initial added moisture
2-*values shown on graphs indicate %AE residue

FIGURE 54, RELATIONSHIP BETWEEN MARSHALL STIFFNESS, S_m, AND PERCENT TOTAL LIQUID, %TL, FOR DIFFERENT AGGREGATE GRADATIONS AND %AE



Legend:
- ■ % retained moisture before water sensitivity test (% WC_{01})
- □ % retained moisture after water sensitivity test (% WC_{02})
- * percent moisture absorption: %MA = % WC_{02} − % WC_{01}

FIGURE 55, INFLUENCE OF AGGREGATE GRADATION ON PERCENT MOISTURE ABSORPTION (%MA) AS A FUNCTION OF DRY CURING TIME
(3.25 %AE, 3% added moisture)

that the other mix components are the same). The percentages of moisture retained in the specimens for the different aggregate gradations before the water sensitivity test were about the same for each curing period; and the variation in $\%WC_o$ before the water sensitivity tests due to varying the gradation was reduced through the curing (Figure 55).

Percent Retained Stability, %P

Figure 56, presents the Marshall stability values as a function of the percent total liquid, at time of test, for both the dry and soaked specimens. The relationships are shown for each aggregate gradation. The percent retained stability is shown between brackets on the soaked condition trends.

The dry Marshall stability increases with decreasing %TL through the curing process, with higher stability values for FG mixes. The percent retained stability for MG mixes was higher than those of FG or CG mixes at all the curing periods. MG aggregate is closer to the maximum density gradation curve (Fuller's maximum density curve) than the other two gradations which could be the main factor in affecting the performance of the AETM.

In addition, for the same percent total liquid that is available in the AETM, the stability values are dependent on the nature or the mechanism of the presence of moisture on the sample (losing moisture through air-dry curing vs. gaining moisture through soaking). This is more apparent for the ultimate cured specimens when subjected to the water sensitivity test (see Figure 56, data points with * identification). The soaked stability values, are much higher than the dry stability values for one day cured specimens, in spite of the fact that the two conditions correspond to about the same percent total liquid.

Percent Retained Stiffness, $\%S_m$

The Marshall stiffness (S_m) responded to the water sensitivity test in the same manner as the stability values (see Figure 57). The MG mixes provided the highest percent retained stiffness ($\frac{S_m \text{ soaked}}{S_m \text{ dry}} \times 100$) as

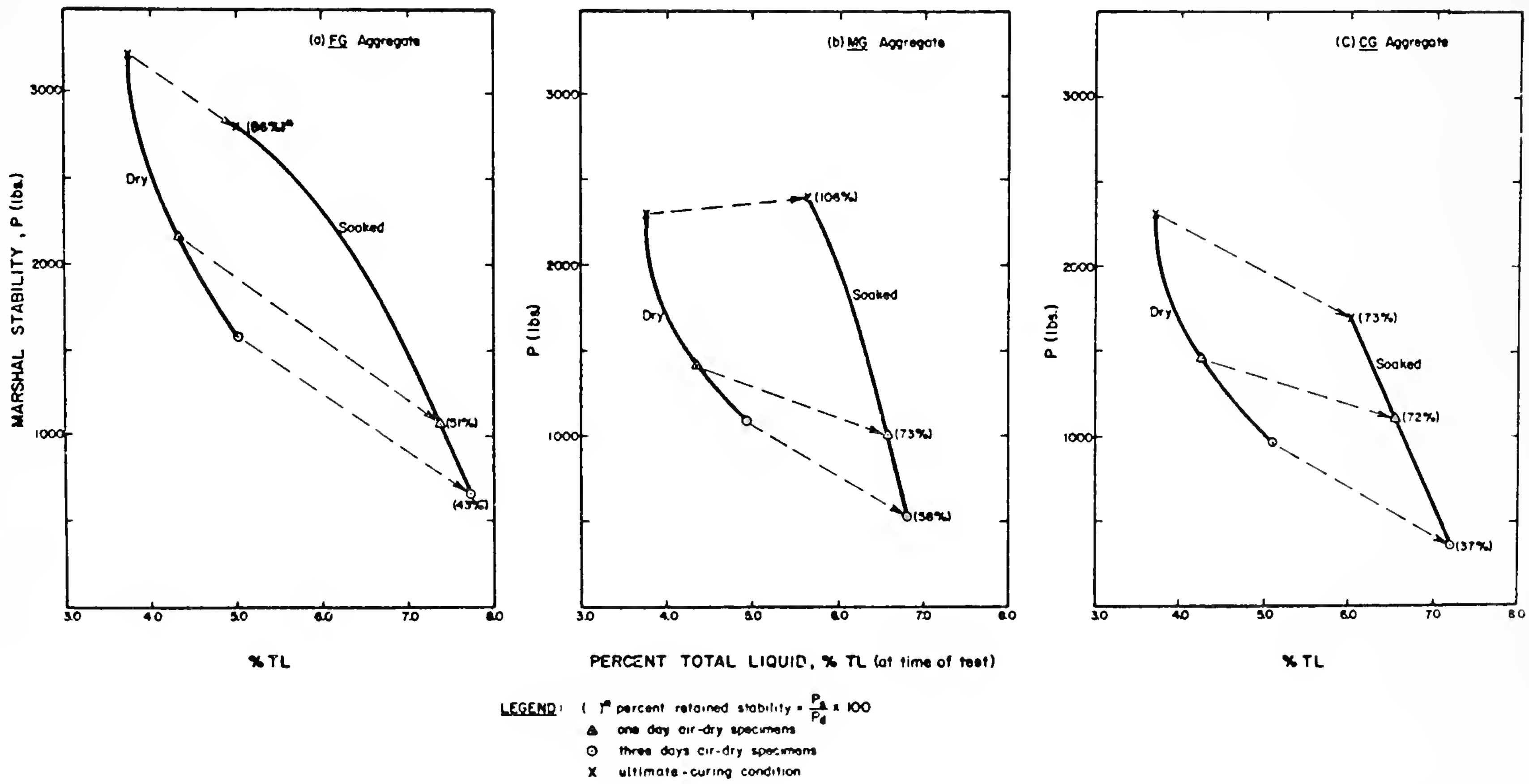


FIGURE 56, MARSHALL STABILITY VALUES AS A FUNCTION OF % TL FOR BOTH AIR-DRY AND SOAKED SPECIMENS (3.25 % AE residue , and 3 % added moisture)

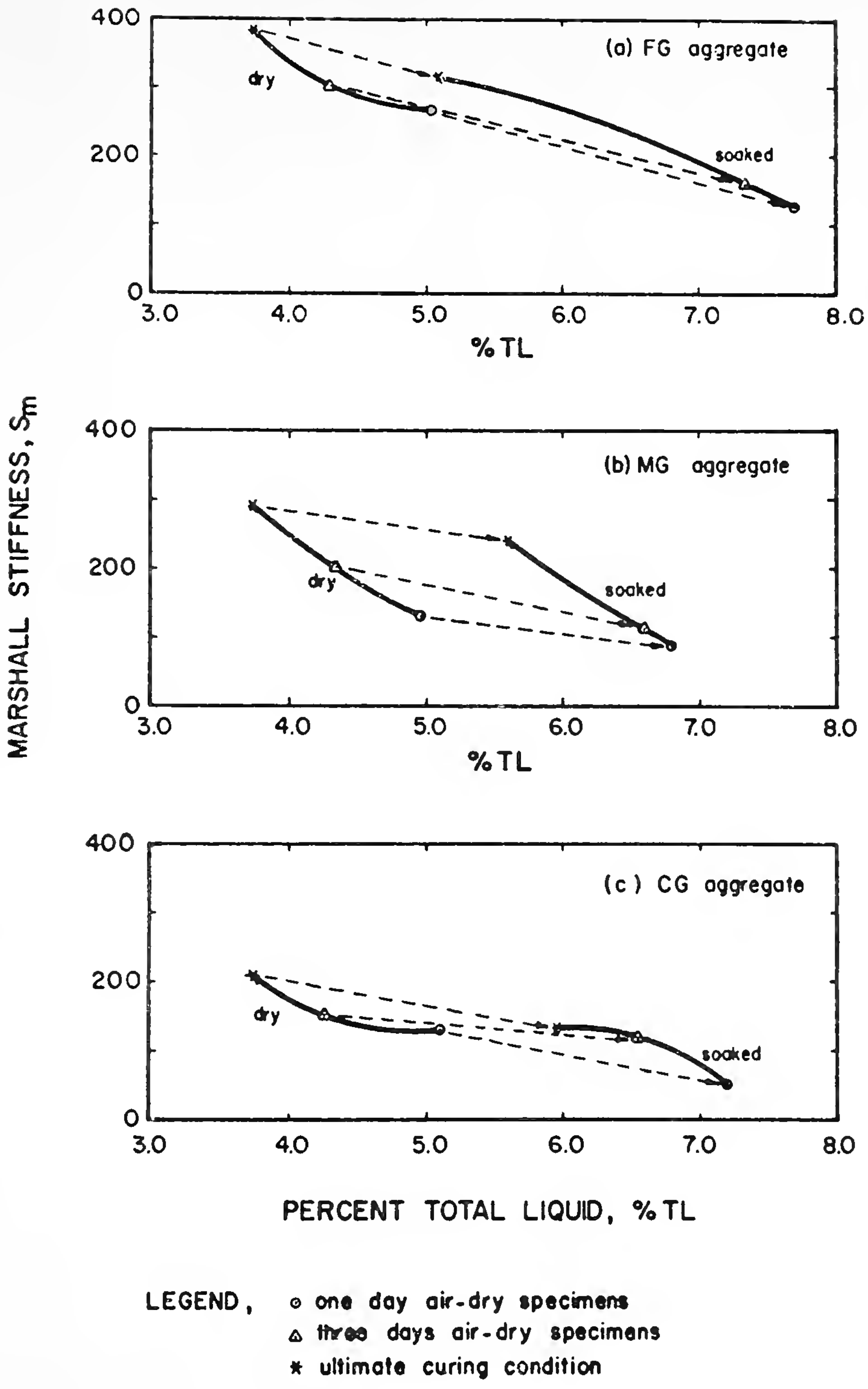


FIGURE 57, MARSHALL STIFFNESS (S_m) AS A FUNCTION OF %TL FOR BOTH AIR-DRY & SOAKED SPECIMENS (3.25% AE, and 3% added moisture)

compared to the FG and CG mixes. The CG mixes showed the least resistance to water damage. In addition, the "S_m vs. %TL" trend was also dependent on the method by which the moisture was present on the AETM system components.

As was suggested before, the dry test results are not enough to provide adequate control and design of the AETM. Water sensitivity results provide a more important indication of the performance of the mix.

Summary of Results

The analysis and evaluation of the test data in this phase of the study revealed a number of significant results that pertain to the effect of aggregate gradation and its interaction effect with the other AETM components on the mix properties. A summary of the main results follows:

1. Aggregate gradation significantly affected all the AETM properties. It should be noted that the three aggregate gradations fall within certain specified gradation limits. This draws attention to the importance of controlling the aggregate gradation in the mix. Designing the AETM through the use of a specific aggregate gradation curve (e.g. mid-point of the specification) does not insure the same performance and properties of the AETM in the field due to the wide band width within the specified aggregate gradation.
2. The significance of the two and higher factor interactions differ and depend on the response variable under consideration (see Table 12).
3. MG and CG aggregate gradations are close to the "theoretical maximum density gradation" which provided an adequate range of particle sizes and resulted in mixes with higher densities and less air voids than the FG mixes.
4. The percent total voids, for a specific mix, was about the same throughout the curing process. The increase in $\%V_A$ through the curing is accompanied by a decrease in $\%V_W$ of about the same magnitude.

5. FG mixes provided the highest stability values throughout the curing process. This was generally accompanied by low flow values when compared with MG or CG mixes.
6. High stiffness indices (I_m and S_m) were obtained for FG mixes when compared to MG or CG mixes. In addition, the "(I_m or S_m) vs. %TL" trends were significantly dependent on the aggregate gradation (Figures 53 and 54).
7. The effect of aggregate gradation on the percent moisture absorption (%MA) depends on the curing state. For the air-dry curing; FG mixes resulted in higher %MA than MG and CG mixes. However, at ultimate condition curing, the FG mixes absorbed the least amount of moisture followed by MG mixes and then the CG mixes.
8. Percent retained stability was higher for MG mixes than those of the FG or CG mixes at all curing levels. The percent retained stability for any mix combination increased through the curing process.
9. The nature of the presence of water in the mix (drying through curing vs. soaking) affects the response parameters of the AETM.

CHAPTER IX: EFFECT OF PORTLAND CEMENT ON AETM PROPERTIES

Introduction

In spite of the potential advantages that can be attained by using AETM, it possesses some relatively unfavorable characteristics especially at an early curing time which limited its use as a high quality paving material. The slow curing rate accompanied by slow development of strength and low resistance to water damage especially at an early curing condition are the main factors of concern when dealing with the AETM. The use of small percentages of portland cement as an additive to the AETM improves these characteristics especially its resistance to water damage.

The interaction effect of portland cement (P.C.) with the different components of the mix system on the performance of AETM was evaluated in this part of the study. One percent of portland cement (1% by weight of the dry aggregate) was used. The portland cement (P.C.) was added to the wet aggregate and mixed immediately before adding the asphalt emulsion (refer to Chapter V for the specimen preparation procedure).

All factors were included in the analysis and evaluation except the percent added moisture (%W) which was fixed to 3%. However, some limited tests were conducted at selected mix combinations that incorporated the use of 1.5% added moisture content (see Table 3). The independent factors used were: additive (no portland cement, and 1.0% P.C.), curing time (1, 3, 7 days and the ultimate curing condition), aggregate gradation (FG, MG, and CG), and %AE residue (2.5, 3.25, and 4.0%). The AETM properties were analyzed within the framework of a fixed-effect randomized complete block design (split-plot design). Since all tests had to be completed at a specified curing time (C) and "with or without" portland cement additive (O) before proceeding to another block of (OC), a restriction on randomization was caused. As a result of this restriction, the tests for the main effects (O) and (C) together with their interaction were not available. However,a statistical test was made utilizing the

true error estimate to evaluate the significance of the restriction for each one of the response variables. A detailed discussion will be presented in the "analysis of results".

Analysis of Results

The following analysis of variance model was used to evaluate the AETM response variables:

$$Y_{ijk\ell m} = \mu + O_i + C_j + OC_{ij} + \delta_{(ij)} + G_k + A_\ell + OG_{ik} + OA_{i\ell} + CG_{jk}$$

$$+ CA_{j\ell} + GA_{k\ell} + OCG_{ijk} + OCA_{ij\ell} + OGA_{ik\ell} + CGA_{jk\ell} + OCGA_{ijk\ell}$$

$$+ \varepsilon_{(ijk\ell)m}$$

where

$Y_{ijk\ m}$ = measured or response variable
μ = overall true mean
O_i = true effect of portland cement additive
C_j = true effect of curing time
$\delta_{(ij)}$ = restriction error, random, NID (o, σ^2)
G_k = true effect of aggregate gradation
A_ℓ = true effect of asphalt emulsion content
$\varepsilon_{(ijk\ell)m}$ = true random error, NID (o, σ^2)

The other terms denote the interactions among the main factors O, C, G, and A. All main effects are fixed. The subscripts assume the values:

$i = 1, 2$
$j = 1, 2, 3, 4$
$k = 1, 2, 3$
$\ell = 1, 2, 3$
$m = 1, 2, 3$

As can be noticed from the analysis of variance model and Table 3 for the factorial design, seventy-two (72) cells or mix combinations were incorporated in this part of the study. The critical Q-values table that accompanied Foster-Burr test for homogeneity of variance included

critical Q-values for a maximum number of 64 samples "cells" (10). The Bartlett's test was inapplicable in this case because the variance in some of the cells was zero. For these reasons the homogeneity of variance of the original data for the various response variables were checked using the control charts for ranges and standard deviations (11). As a result, the homogeneity of variance was accepted for the original data of the response variables: γ_d, γ_w, P, F, and I_m. A logarithmic transformation for S_m data was necessary. The homogeneity of variance was accepted for the $\%WC_o$ original data after excluding one observation from each of four cells due to their large variances that exceeded the critical limits on the control charts for cell standard deviations and ranges (11).

Table 13, presents a summary of the analysis of variance results for the AETM response variables. In addition, the results of applying the expected mean square algorithm (2) to the ANOVA model and a typical ANOVA table for two of the response variables are shown in Tables B4 through B6 in the appendices.

The restriction error pointed out earlier can be noticed from the terms included in the expected mean squares (Table B4, in the Appendices). Owing to this restriction error, tests were not available for evaluating the significance of O, C, and OC interaction effect. However, a conservative test was made utilizing the true error estimate for the three sources of variation (O, C, and OC). That is, if any of the three treatments turned out not significant it definitely was not significant and the null hypothesis H_o: $\sigma_\delta^2 + \phi(\ ) = 0$ was accepted. As a result, the restriction on randomization (blocking effect) was not significant and the restriction error effect (σ_δ^2) was assumed zero. In this case, tests on the other two sources were conducted. Table B6 in the appendices shows the ANOVA table for I_m data in which this concept was used. For more detailed information and discussion of the restriction error concept the reader is referred to Anderson and McLean (2).

The following sections present the results and evaluation of each of the AETM response variables. The results of the water sensitivity tests for this portion of the study are presented at the end of this chapter.

TABLE 13, SUMMARY OF ANOVA RESULTS FOR AETM PROPERTIES (phase 2; design 3)

Source of Variation \ Response Variables	γ_d	γ_w	$\%WC_o$	P	F	I_m	$\log_{10}S_m$
O	S+	—	—	—	N.S.+	S+	N.S.+
C	N.S.+	—	—	—	S+	S+	S+
OC	S+	—	—	—	S+	N.S.+	S+
G	S	S	S	S	S	S	S
A	S	S	S	S	S	S	S
OG	N.S.	S	S	S	N.S.	S	S
OA	S	S	S	S	N.S.	N.S.	S
CG	S	S	S	S	S	S	S
CA	S	S	S	S	S	S	S
GA	N.S.	N.S.	S	N.S.	S	S	S
OCG	S	S	S	N.S.	N.S.	S	N.S.
OCA	N.S.	N.S.	S	N.S.	N.S.	S	N.S.
OGA	S	N.S.	S	S	S	S	S
CGA	S	S	S	S	S	N.S.	S
OCGA	S	S	S	S	S	S	S

NOTE:

1 - S = Significant at $\alpha = 0.05$

2 - N.S. = Not significant at $\alpha = 0.05$

3 - — = No test avaliable

4 - + = Indirect test, see discussion on page 128.

Percent of Moisture Retained in the Sample, $\%WC_o$

During the mixing and preparation procedure, the mixtures that contained 1% portland cement (P.C.) appeared wetter and had relatively less of a coating than the mixtures prepared without portland cement additive. However, the cement-treated AETM appeared relatively drier during testing. Generally, this had been the case for all mix combinations.

The test results showed that the percent moisture retained in the sample ($\%WC_o$) was higher for "cement-treated AETM"* samples than those obtained for the AETM. Figure 58 presents the average percent moisture retained for AETM and cement-treated AETM samples. Each data point in the graph represents the average $\%WC_o$ of the three cells (different %AE) at each curing time and aggregate gradation. The difference in $\%WC_o$ was about 0.5% after one day curing for all aggregate gradations. This difference decreased as curing progressed.

Dry Unit Weight, (γ_d)

The use of 1% portland cement in the AETM significantly affected the dry unit weights of the mixtures. In general, the AETM samples possessed higher γ_d than those of the cement-treated AETM. In addition, the results of the ANOVA indicate that most of the interaction effects significantly affected the dry unit weight values (see Table 13). This necessitates evaluating and understanding the role of each factor and their interaction effects. Figure 59 presents the dry unit weight values (γ_d) for both AETM and cement-treated AETM as a function of curing time, aggregate gradation, and percent asphalt emulsion. It can be seen from this figure that the general trend of the effect of P.C. (decrease in γ_d) does not hold for all mix combinations. In a few cases, the cement-treated AETM provided higher dry unit weights. This is more apparent for mixes containing FG aggregate after seven days air-dry curing.

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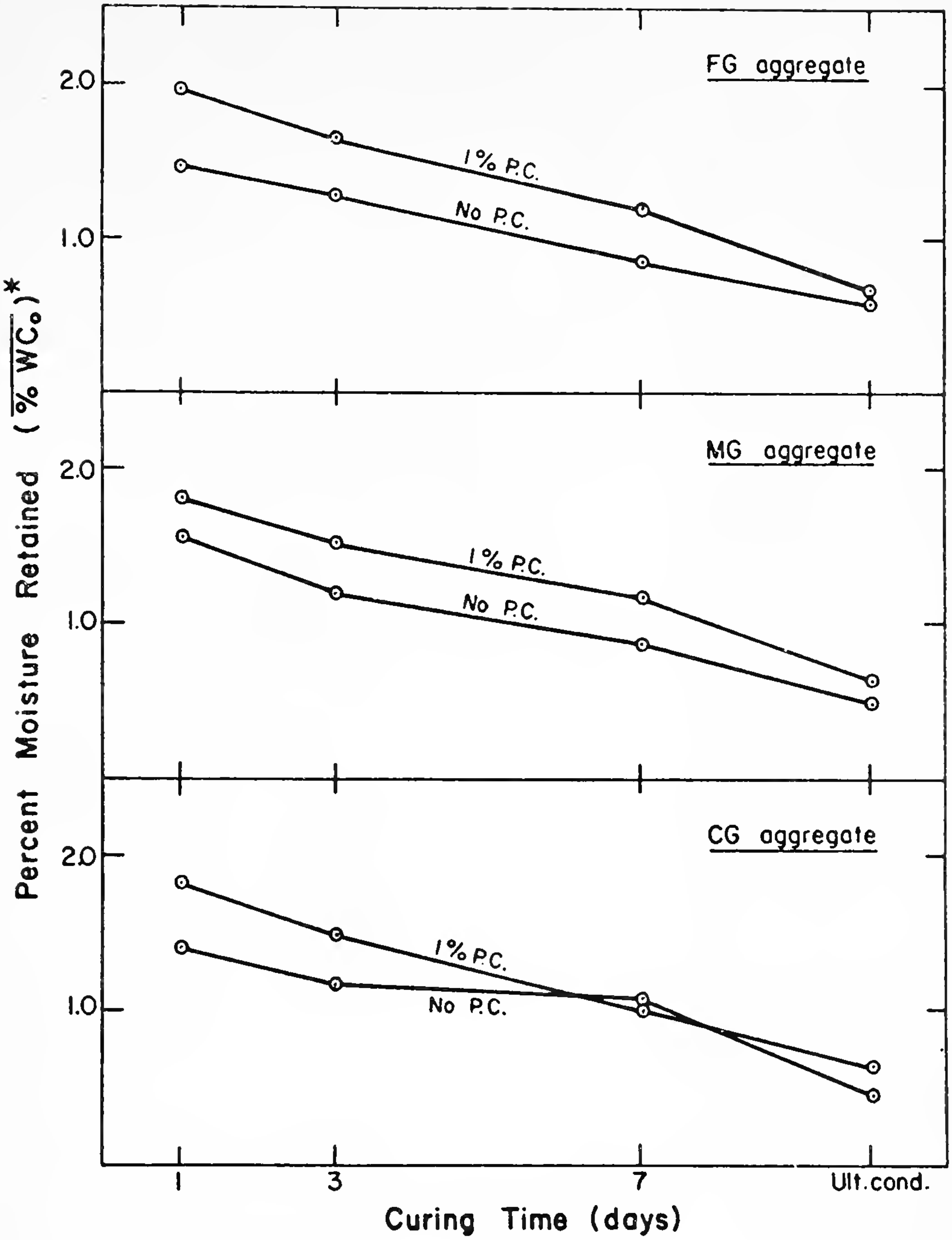
*The term "Cement-treated AETM" refers to AETM that contains 1% portland cement.



NOTE:

1. 3% added moisture for all test samples
2. *each data point in the graph represent the average $\%WC_o$ of the 3 mix combinations that contained different %AE

FIGURE 58, EFFECT OF PORTLAND-CEMENT (P.C.) ON PERCENT MOISTURE RETAINED IN THE SAMPLE

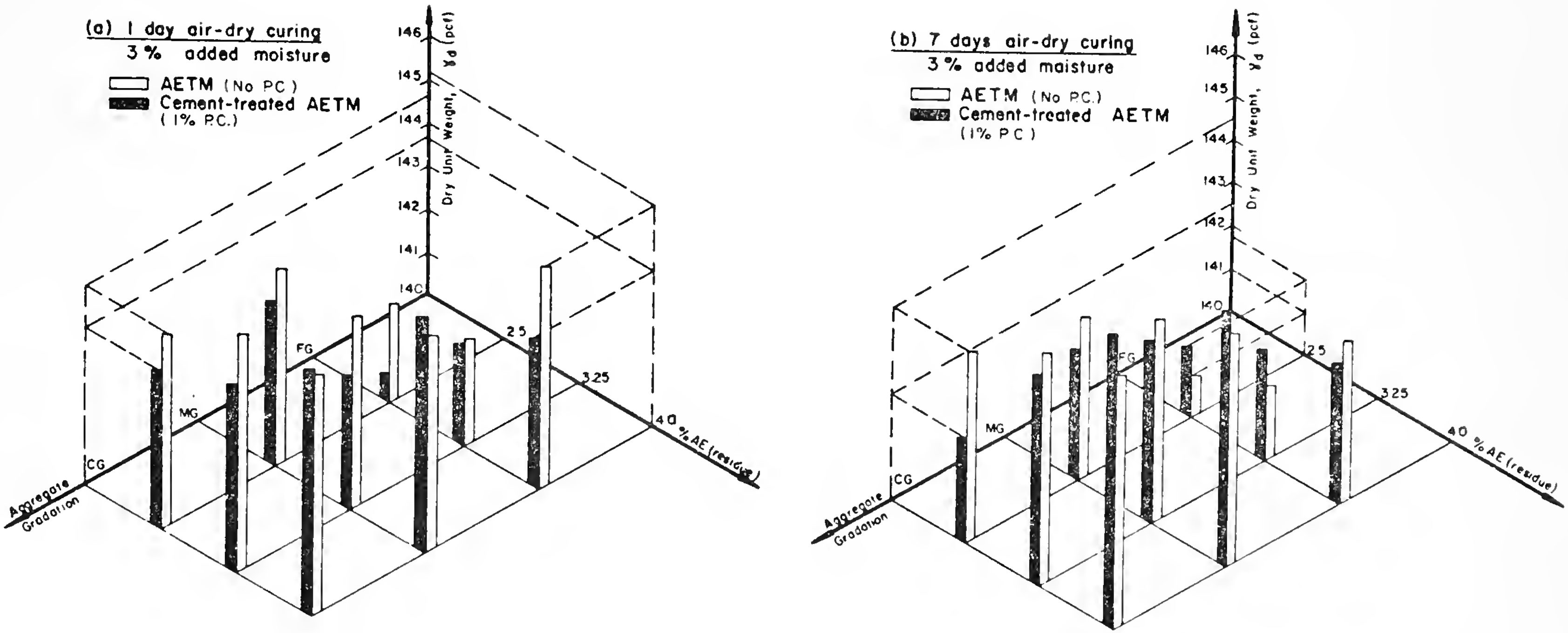


FIGURE 59, INFLUENCE OF PORTLAND-CEMENT ON THE DRY UNIT WEIGHT (γ_d) AS A FUNCTION OF AGGREGATE GRADATION, AND %AE RESIDUE

Marshall Stability, P

The results of the ANOVA are shown in Table 13. It is of interest to note the significant interaction effect of the portland cement (P.C.) with aggregate gradation and %AE used. The effect of P.C. on Marshall Stability values is influenced by the aggregate gradation and %AE. The effect of interaction among curing time, aggregate gradation, %AE, and P.C. on Marshall stability values is shown in Figure 60. For one-day cured specimens, the effect of P.C. is more significant for mixes that contained MG aggregate. Also, at low asphalt emulsion contents, the effect of P.C. is more apparent and it improved the mix stability for all the aggregate gradations. However, by increasing the %AE in the mix the aggregate gradation starts influencing the role of P.C. on the mix and reduces its effect. In case of using CG aggregate, the use of P.C. did not improve the stability of the mix and in most cases it provided a reverse effect. This reduction in stability of CG aggregate mixes due to the use of P.C. could be expected due to the relatively poor coating that was attained when using coarse gradation aggregate with P.C.

The effect of P.C. was more apparent at the early curing condition. After relatively long periods of curing the use of P.C. resulted in an increase in stability but not with the same degree as for early cured samples (see 7-day curing results, Figure 60). The effect of aggregate gradation on the role of P.C. in the mix after 7-days curing was reduced as compared to its effect for one-day cured samples.

As was pointed out earlier, the AETM response parameters are dependent on the percent total liquid (%TL) that is available in the mix at time of testing. Cement-treated AETM held more retained moisture than the AETM, consequently the %TL was more for samples treated with P.C. In spite of the increase in %TL for cement-treated AETM as compared to AETM, a gain in stability occurred in most of the cases depending on the aggregate gradation used. The significant effect on stability that is obtained by the use of 1% P.C. can be seen in Figure 61 where the stability results of the cement-treated AETM are presented together with those of the AETM as a function of percent total liquid at time of testing. The change in %TL was obtained through the curing process. For FG and MG

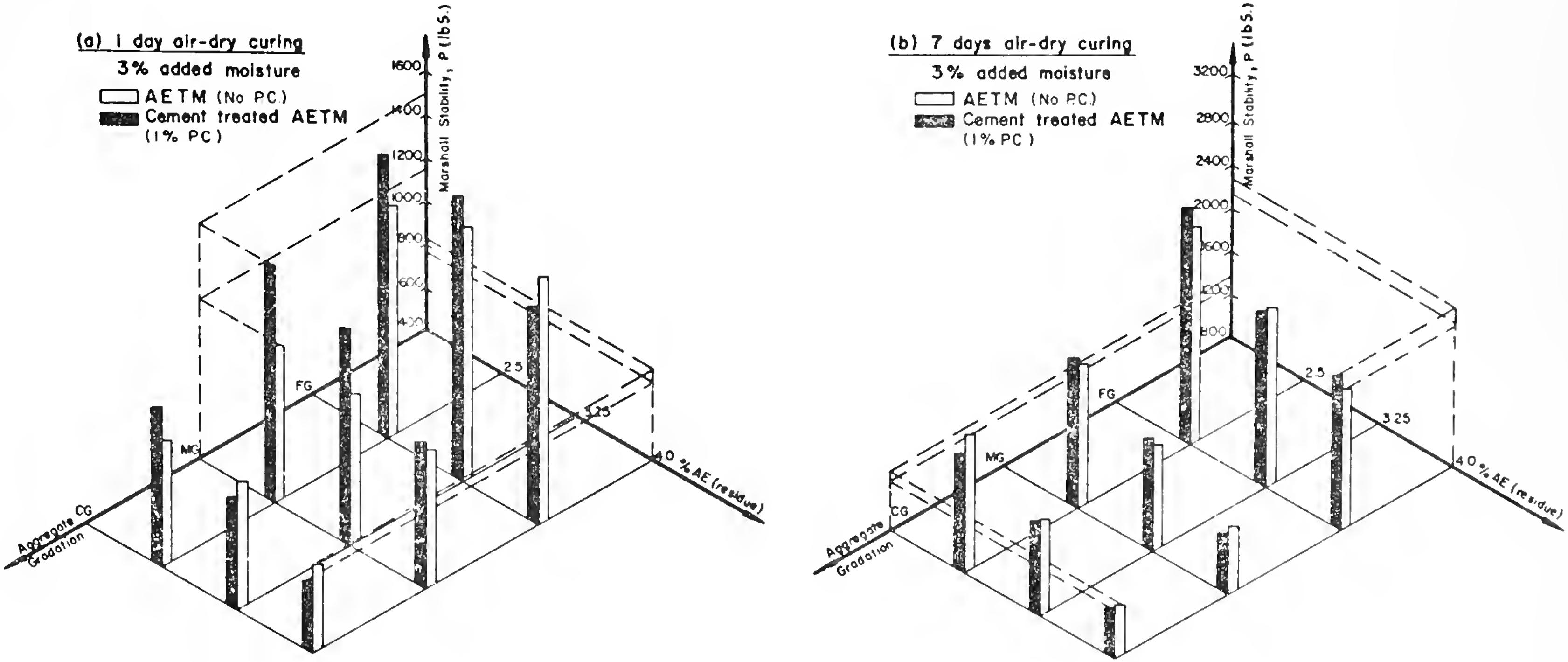


FIGURE 60, INFLUENCE OF PORTLAND-CEMENT ON MARSHALL STABILITY (P) AS A FUNCTION OF AGGREGATE GRADATION, AND %AE RESIDUE

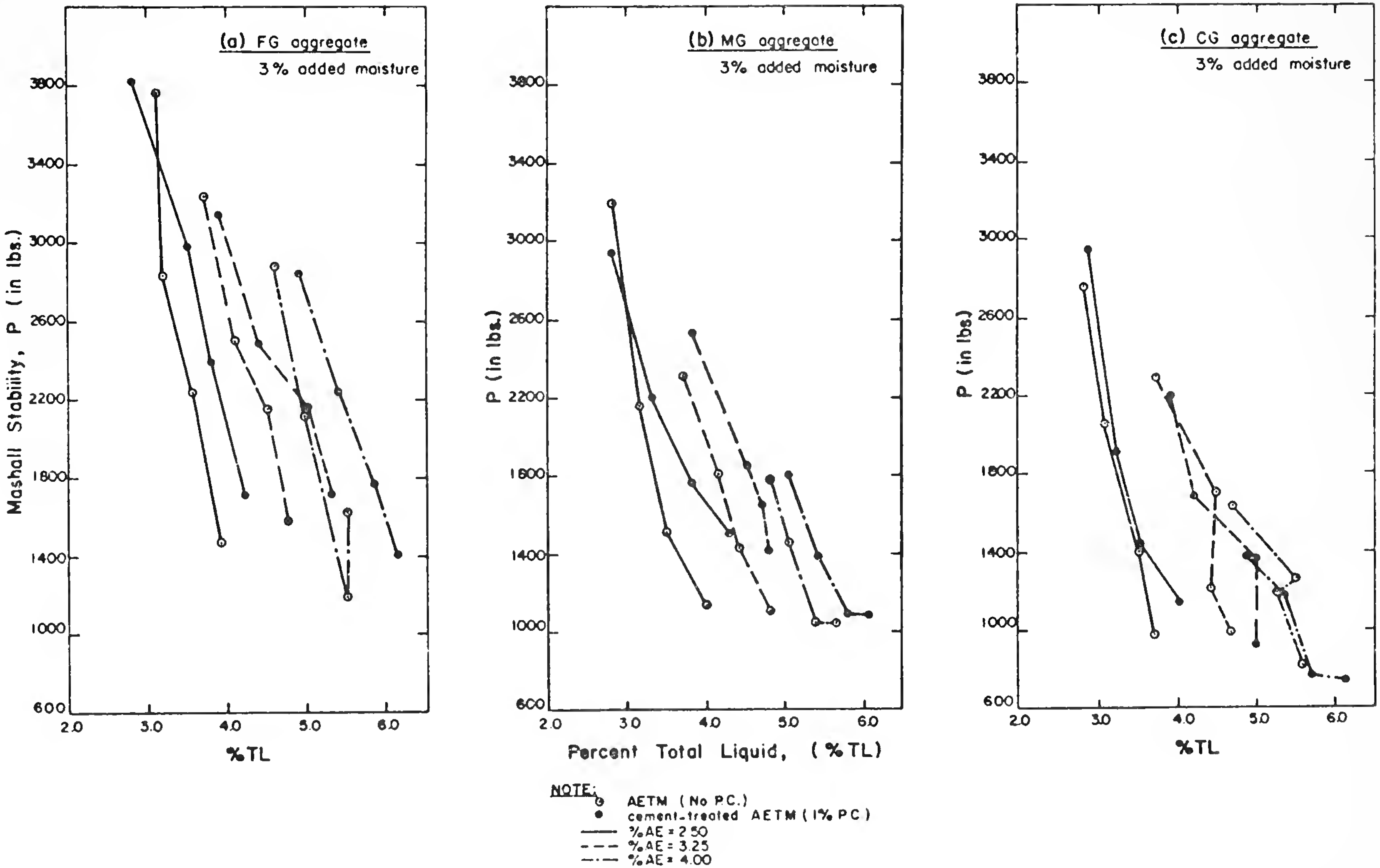


FIGURE 61, MARSHALL STABILITY (P) AS A FUNCTION OF PERCENT TOTAL LIQUID (%TL) FOR AETM AND CEMENT-TREATED AETM

aggregate mixes a substantial increase in stability was obtained by the use of 1% portland cement. That is, at a specific %TL the cement-treated AETM provided a large increase in stability as compared to AETM. However, the use of P.C. with CG aggregate mixes was not beneficial especially at high %AE where a drop in stability occurred.

Marshall Flow, F

The flow values were not significantly affected by the use of portland-cement as an additive to the AETM. Figure 62 presents the flow values data for one and seven days of curing. It can be noticed that generally the use of P.C. reduced the flow values for most of the mix combinations, however, this difference is not significant. This resulted mainly due to the fact that the use of P.C. produced a reduction, or in some cases a slight increase, in flow values that could be expected as a variation within the three replicates of the mix. Also, the P.C. factor and its interaction with aggregate gradation or %AE were not significant (Table 13).

Air Voids ($\%V_A$) and Total Voids ($\%V_T$)

Percent air voids and total voids were not affected appreciably by the use of portland cement. The manner in which P.C. affected the results was mainly dependent on the aggregate gradation and %AE in the mix (see Figure 63 and 64). The air voids were higher for CG aggregate mixes when treated with P.C. than the untreated specimens. However, the FG aggregate mixes showed a reverse reaction, that is, lower air voids for cement-treated AETM than the AETM. The percent air voids is inversely related to the mix unit weight, which is more apparent when comparing the air void results with that of the dry unit weight results for the different mix combinations that was discussed earlier in this chapter.

Study of the total voids ($\%V_T$) indicated that the use of portland cement provided, in general, an increase in $\%V_T$. This increase in $\%V_T$ is attributed to the observed increase in the amount of retained moisture when using P.C. in the mix which was discussed earlier. A note of caution has to be mentioned again; the variations or differences in

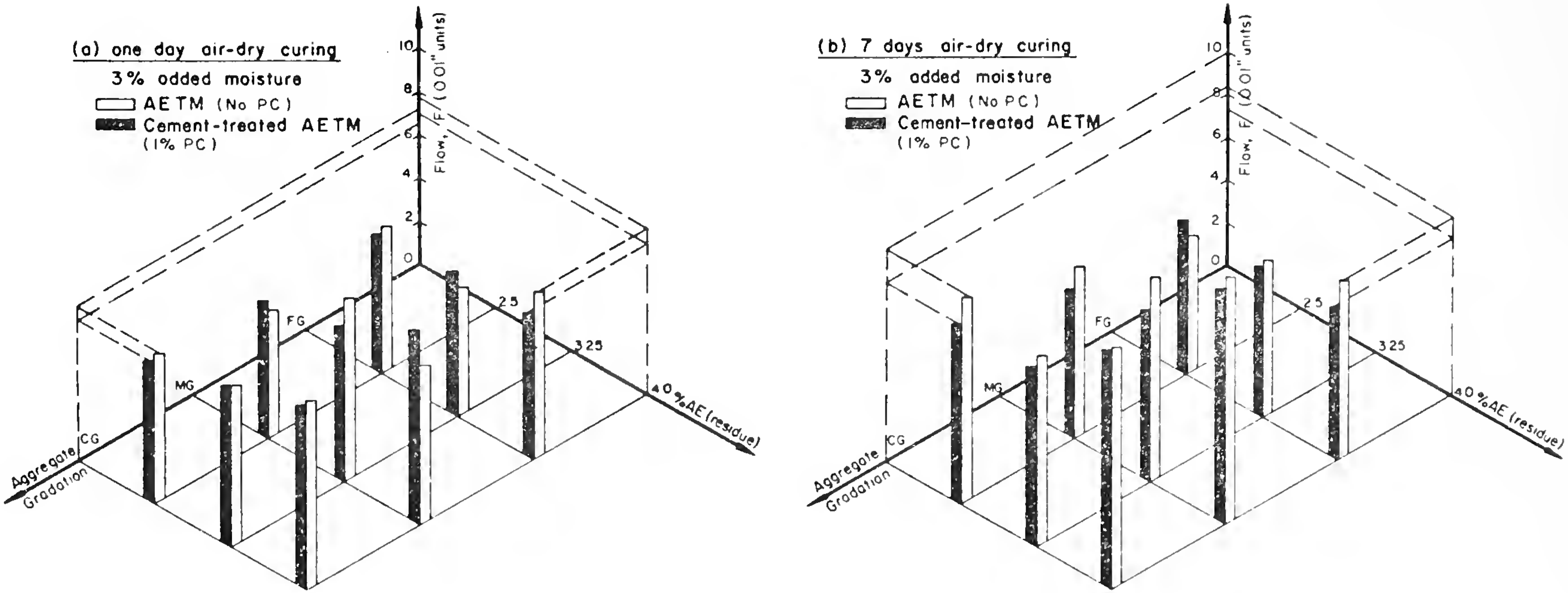


FIGURE 62, INFLUENCE OF PORTLAND-CEMENT ON MARSHALL FLOW VALUES (F) AS A FUNCTION OF AGGREGATE GRADATION AND %AE RESIDUE

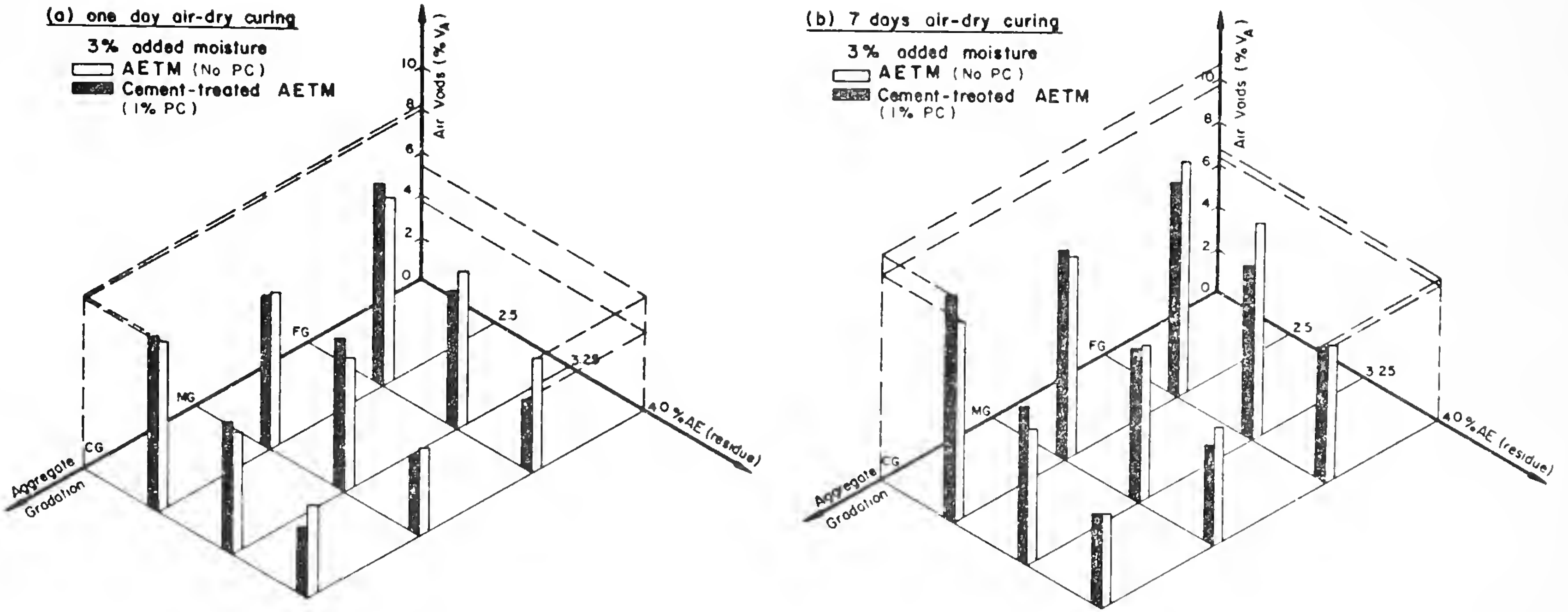


FIGURE 63, INFLUENCE OF PORTLAND-CEMENT ON PERCENT AIR VOIDS (% V_A) AS A FUNCTION OF AGGREGATE GRADATION AND %AE RESIDUE

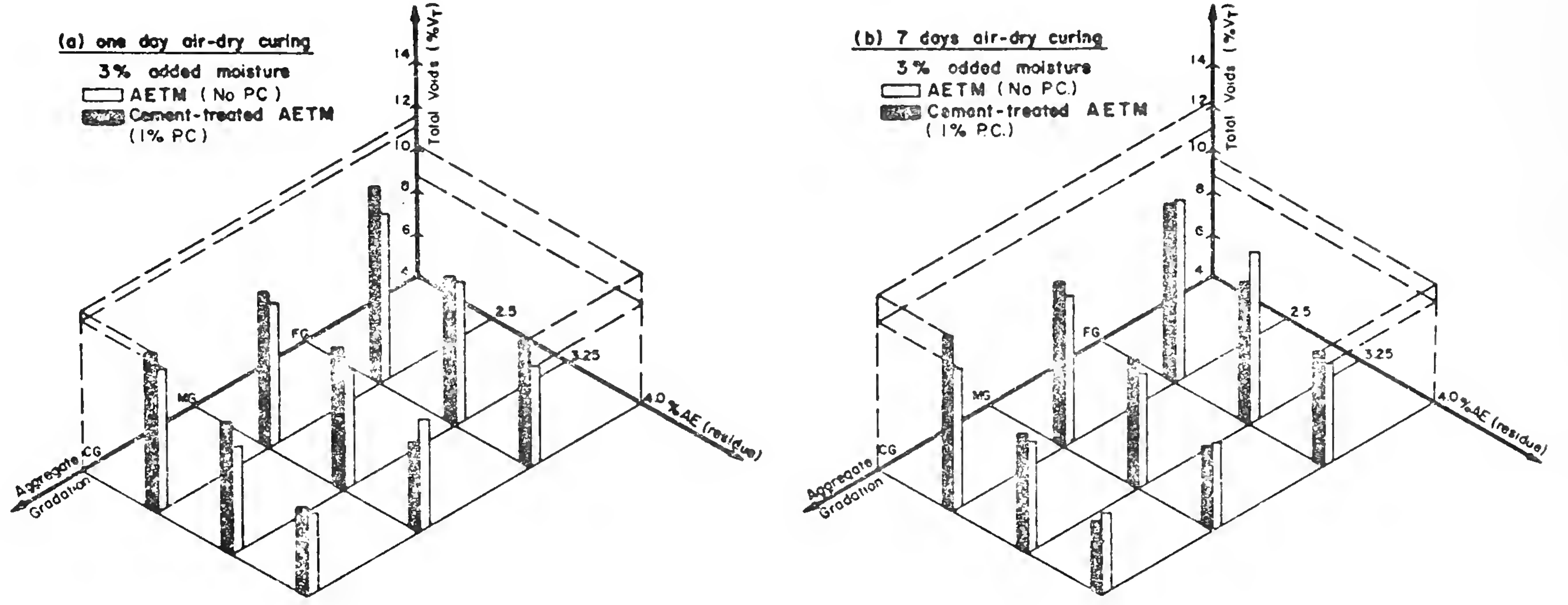


FIGURE 64, INFLUENCE OF PORTLAND-CEMENT ON PERCENT TOTAL VOIDS (%V_T) AS A FUNCTION OF AGGREGATE GRADATION AND %AE RESIDUE

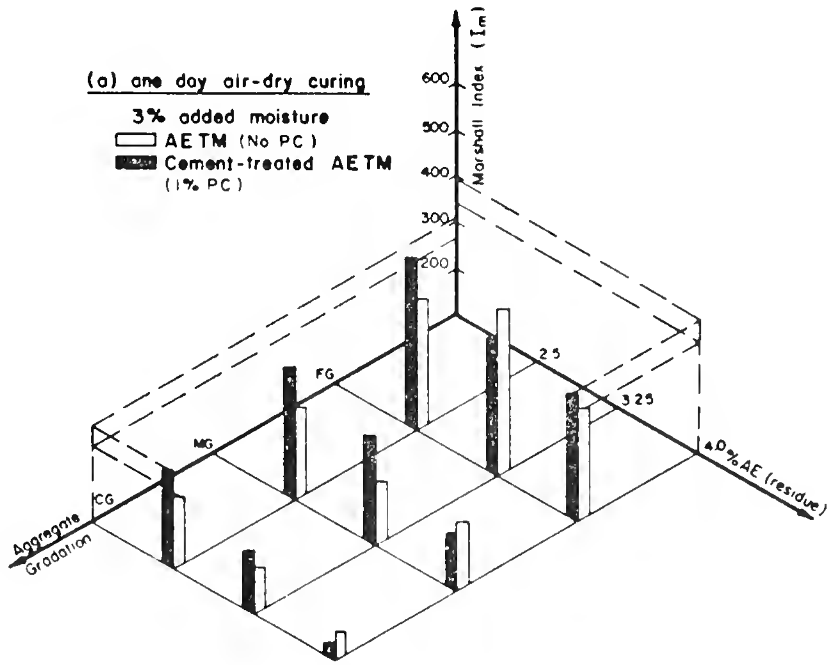
$\%V_A$ and $\%V_T$ due to the use of P.C. are not of significant value. The maximum difference in $\%V_A$ (cement-treated AETM vs. AETM) was about 2% with most of the differences in the range of 1%. The difference in $\%V_T$ was in the range of about $\pm$ 1%.

Marshall Stiffness (S_m) and Marshall Index (I_m)

The summary of the ANOVA results was presented in Table 13. In analyzing these two response variables a logarithmic transformation was applied to the original data of S_m to satisfy the requirement of homogeneity of variance, a usual assumption in analysis of variance.

The use of P.C. in AETM together with the other main factors under study signfiicantly affected the I_m values, but the interaction effect of P.C. with %AE was not significant (Table 13). However, the $\log S_m$ values were not significantly affected by the use of P.C. in the AETM. This resulted from the nature of the S_m variable which is obtained by the direct relation $S_m = \frac{P}{F}$. The flow values (F) were not significantly affected by P.C. and they were taking a random trend in their variation in such a way that they reduced, statistically, the role of P.C. on Marshall stiffness (S_m). On the other hand, all two-factor interactions were significant.

Figures 65 and 66 present the Marshall Index and stiffness values, respectively, as a function of the aggregate gradation, and %AE residue for the two curing periods one and seven days. For one day cured specimens, the I_m values increased when P.C. was used in the AETM especially at a low %AE. The P.C. effect was reduced at high %AE (e.g. 4%). In addition, aggregate gradations show a significant role in affecting the role of P.C. in the mix. The test data for 7 days cured specimens (Figure 65(b)) show that the cement-treated AETM possessed higher values as compared to the AETM in almost all the mix combinations. The gain in I_m values due to the use of P.C. was decreased through the curing process. This leads to the conclusion that although the effect of P.C. on I_m values at early curing periods varies and depends on the aggregate gradation and %AE, its effect after relatively longer periods is beneficial (as far as the increase in I_m is concerned) at almost all levels of aggregate gradation and %AE.



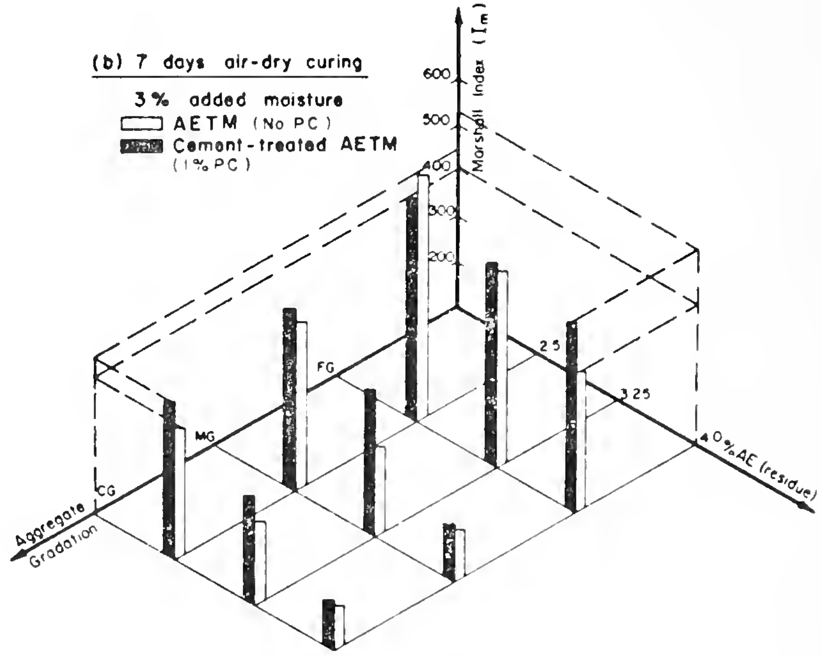


FIGURE 65, INFLUENCE OF PORTLAND-CEMENT ON MARSHALL INDEX (I_m) AS A FUNCTION OF AGGREGATE GRADATION AND %AE RESIDUE

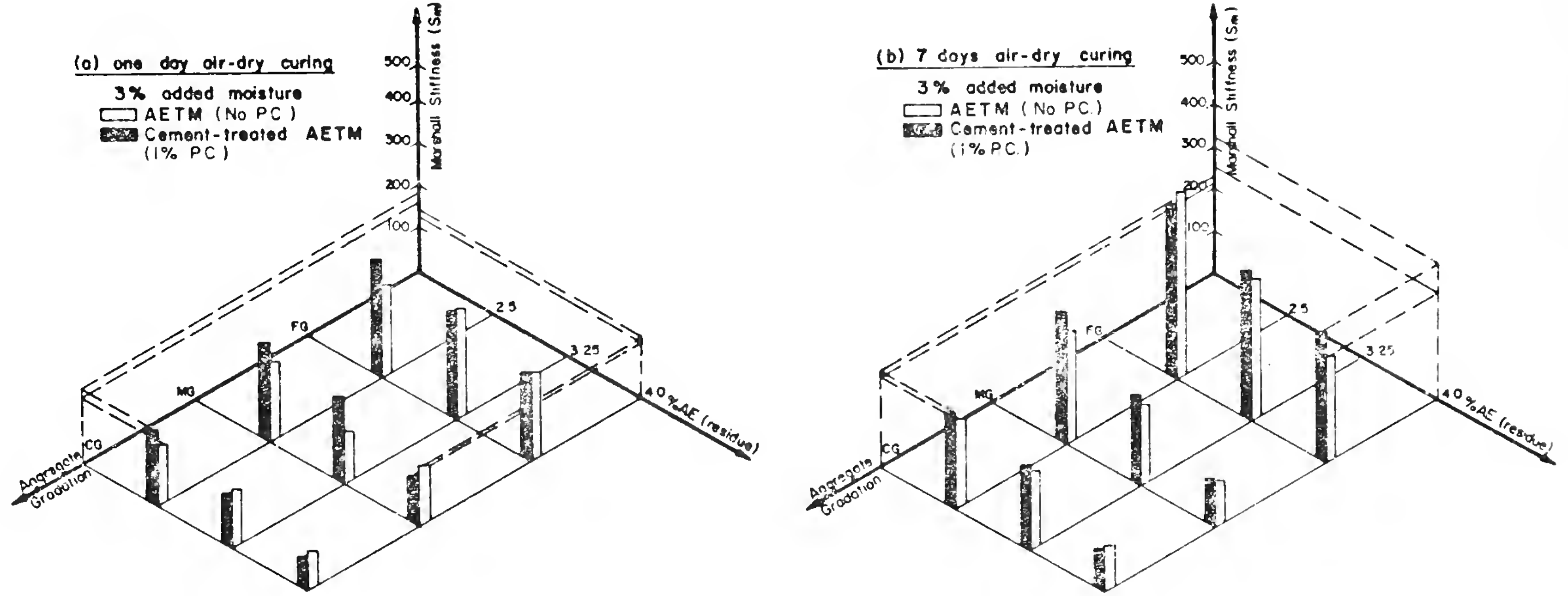


FIGURE 66, INFLUENCE OF PORTLAND-CEMENT ON MARSHALL STIFFNESS (S_m) AS A FUNCTION OF AGGREGATE GRADATION AND %AE RESIDUE

The Marshall stiffness (S_m), followed approximately the same trend as the Marshall Index (I_m) but its response (change in S_m values) to the use of P.C. was less pronounced than the I_m values. As mentioned before, this is due to the difference in nature between the two stiffness measures. I_m provides a measure of the mix characteristics during the duration of loading while S_m is a measure of the mix characteristics at the failure condition and is directly related to the stability and flow values of the mix.

The Marshall index (I_m) as a function of percent total liquid (%TL) is presented in Figure 67. The trends were obtained by utilizing the test results at different curing periods. An increase in the I_m values was obtained by using 1% P.C. as an additive to the AETM. At a specific %TL available in the specimen, the cement-treated AETM provided a pronounced and significant increase in I_m. The effect of P.C. is also dependent mainly on the aggregate gradation and %AE residue. No gain in I_m or S_m was obtained when using CG aggregate especially with high %AE.

Water Sensitivity Test Results

Most of the water sensitivity tests were conducted for mix combinations that contained MG aggregate at two curing periods; one and three days air-dry curing. Other mix combinations that contained FG and CG aggregate were selected for comparison purposes (as shown earlier in Table 3) for mix combinations that contained 3.25% AE, and 3% added moisture. Following is a summary of the water sensitivity test results.

Percent Moisture Absorption (%MA)

Cement-treated AETM as depicted in Figure 68 (for MG mixes) have less moisture absorption than the AETM without portland cement. The effect of P.C. in reducing percent moisture absorption was more apparent at low %AE and decreases with the increase in %AE. Adding P.C. to the AETM improves the bonding between the AETM components and consequently reduces the amount of moisture that is permitted to enter through the system. Also, Figure 69 shows that the effect of P.C. was beneficial for all the three aggregate gradations in reducing %MA. FG aggregate mixes

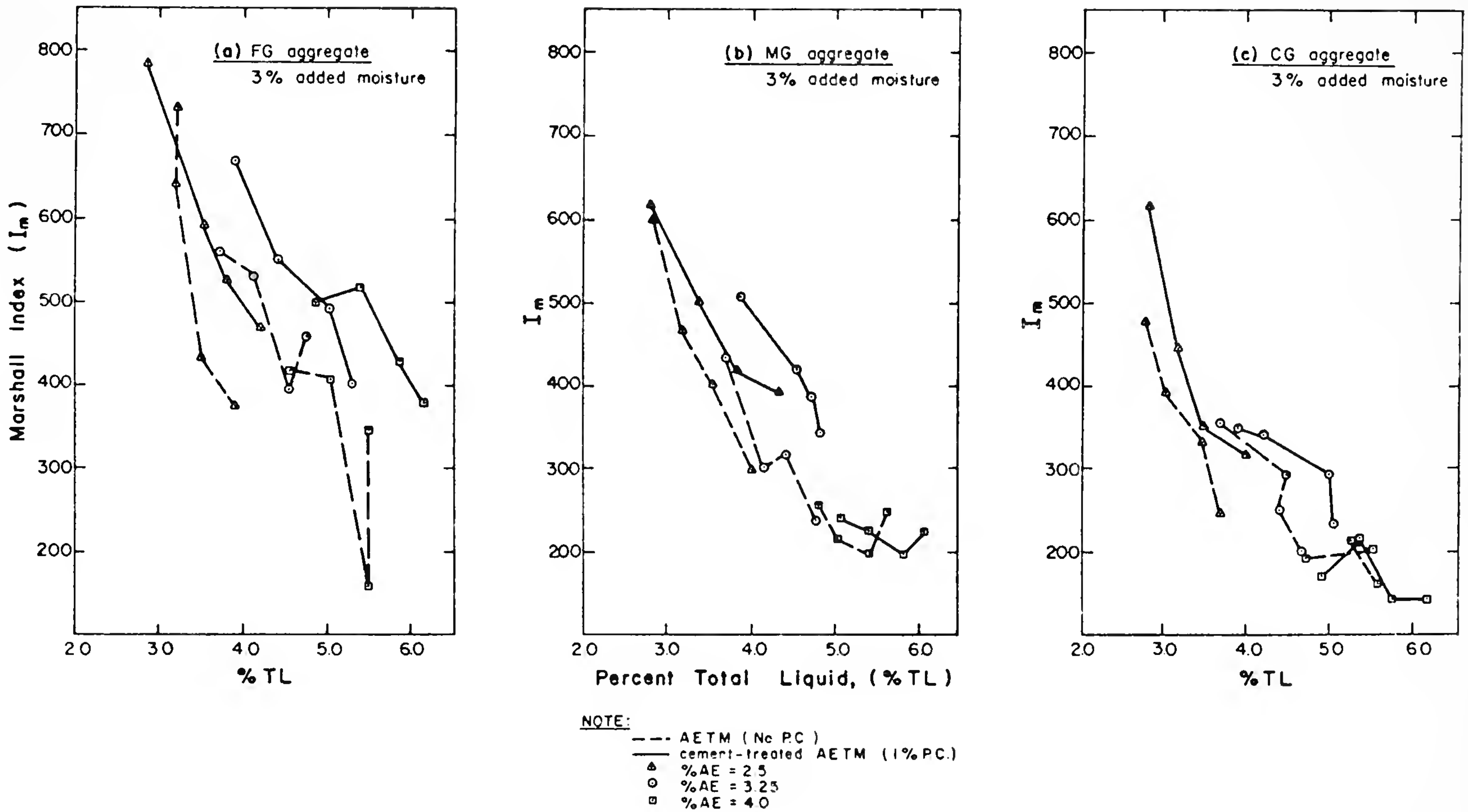


FIGURE 67, MARSHALL INDEX (I_m) AS A FUNCTION OF PERCENT TOTAL LIQUID (%TL) FOR AETM AND CEMENT-TREATED AETM

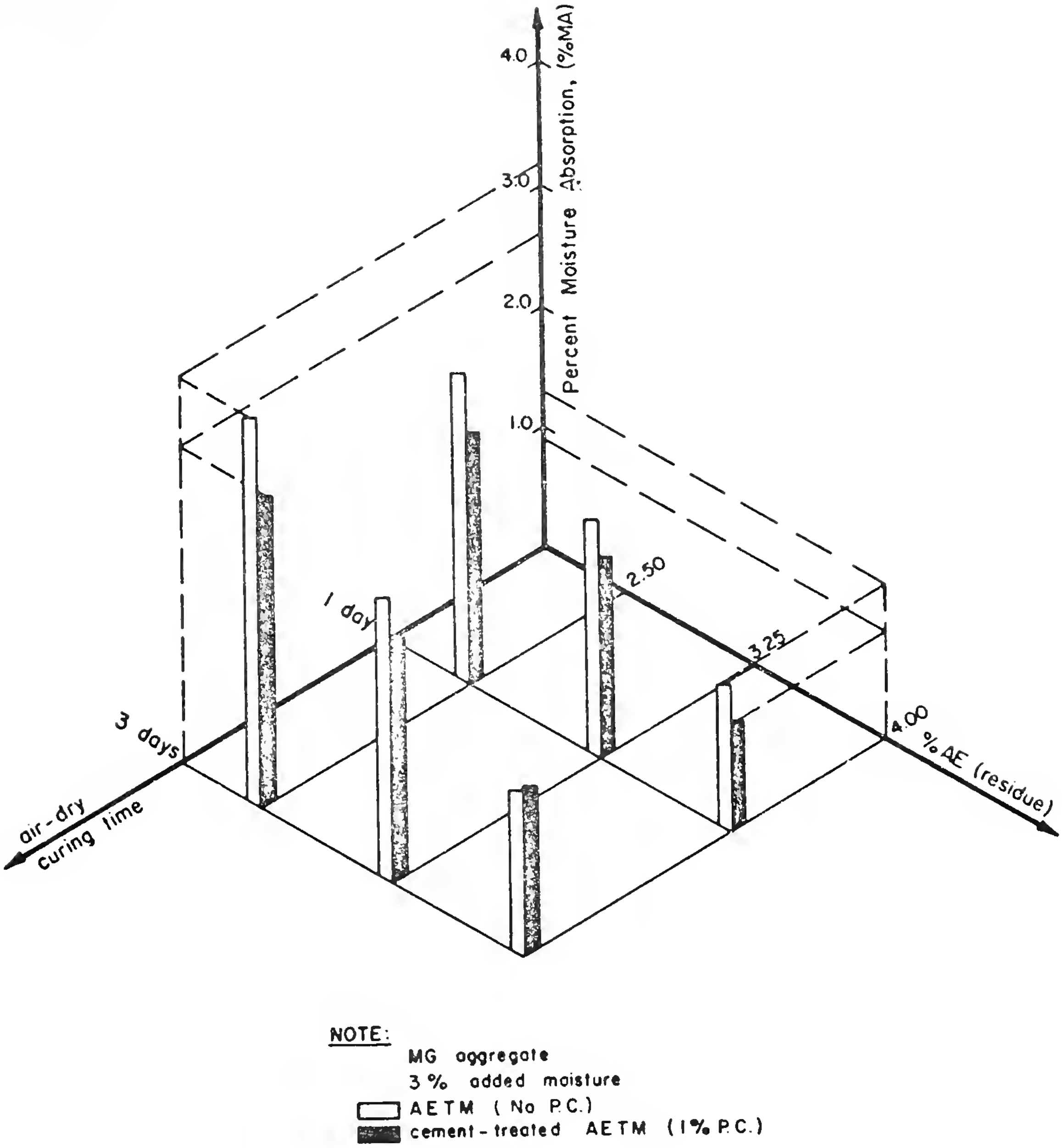
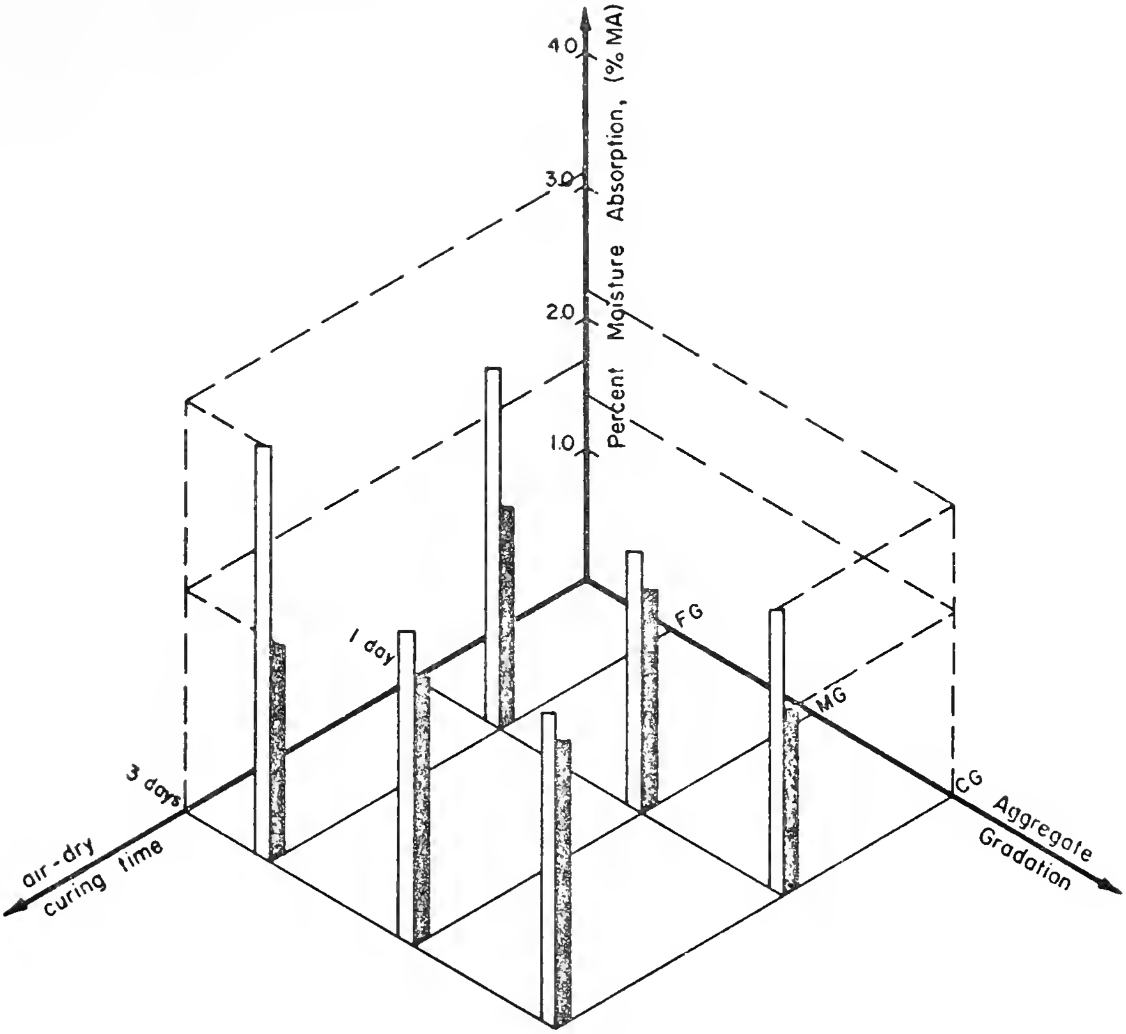


FIGURE 68, PERCENT MOISTURE ABSORPTION (%MA) FOR AETM AND CEMENT-TREATED AETM SPECIMENS



NOTE:
3.25 % AE residue
3.0 % added moisture
AETM (No P.C.)
cement - treated AETM (1% P.C.)

FIGURE 69, EFFECT OF PORTLAND-CEMENT ON PERCENT MOISTURE ABSORPTION (%MA) FOR THE DIFFERENT AGGREGATE GRADATIONS

resulted in the largest reduction in %MA when treated with portland cement. It should be noticed that the data on Figure 69 are for mixes that contained 3.25% AE and 3% added moisture. The reduction in the percent moisture absorbed through the use of P.C. resulted in less percent total liquid (%TL) available in the cement-treated AETM than the AETM. This in turn contributed to the higher retained "strength" parameters that were obtained for the cement-treated AETM.

Percent Retained Stability, %P

The use of 1% P.C. had a pronounced effect in improving the retained stability for the AETM. An appreciation of the effect of using 1% P.C. as an additive to AETM can be obtained by study of Figure 70, in which the dry and soaked stability results for AETM and cement-treated AETM at two different curing times are presented. The percent retained stability for mixes that contained MG aggregate increased to a range of 75 to 81 percent for one day cured specimens as compared to the range of 41 to 58 percent for untreated AETM. For three days cured specimens the range was 79 to 92 percent as compared to 69 to 81 percent for AETM without portland cement additive. The asphalt emulsion content affected the role of portland cement. The significant effect of P.C. was more pronounced at low %AE (e.g. 2.5%). Percent retained stability for AETM increased with increasing %AE, however for the cement-treated AETM the percent retained stability decreased with increasing %AE. This can be seen by comparing the soaked stability trends for AETM and cement-treated AETM (Figure 70).

In addition, mixes made with FG or CG aggregate are shown to gain resistance to water damage when treated with portland-cement (see Figure 71). In an earlier discussion that dealt with the effect of P.C. on the dry stability of AETM, it was shown that the CG aggregate mixes did not show an appreciable gain in stability through the use of Portland Cement (and in some mix combinations it showed a slight decrease in stability). However, it is of interest to note the important effect of using P.C. with CG aggregate mixes which improved appreciably its resistance to water damage. This provides another example for the importance of the

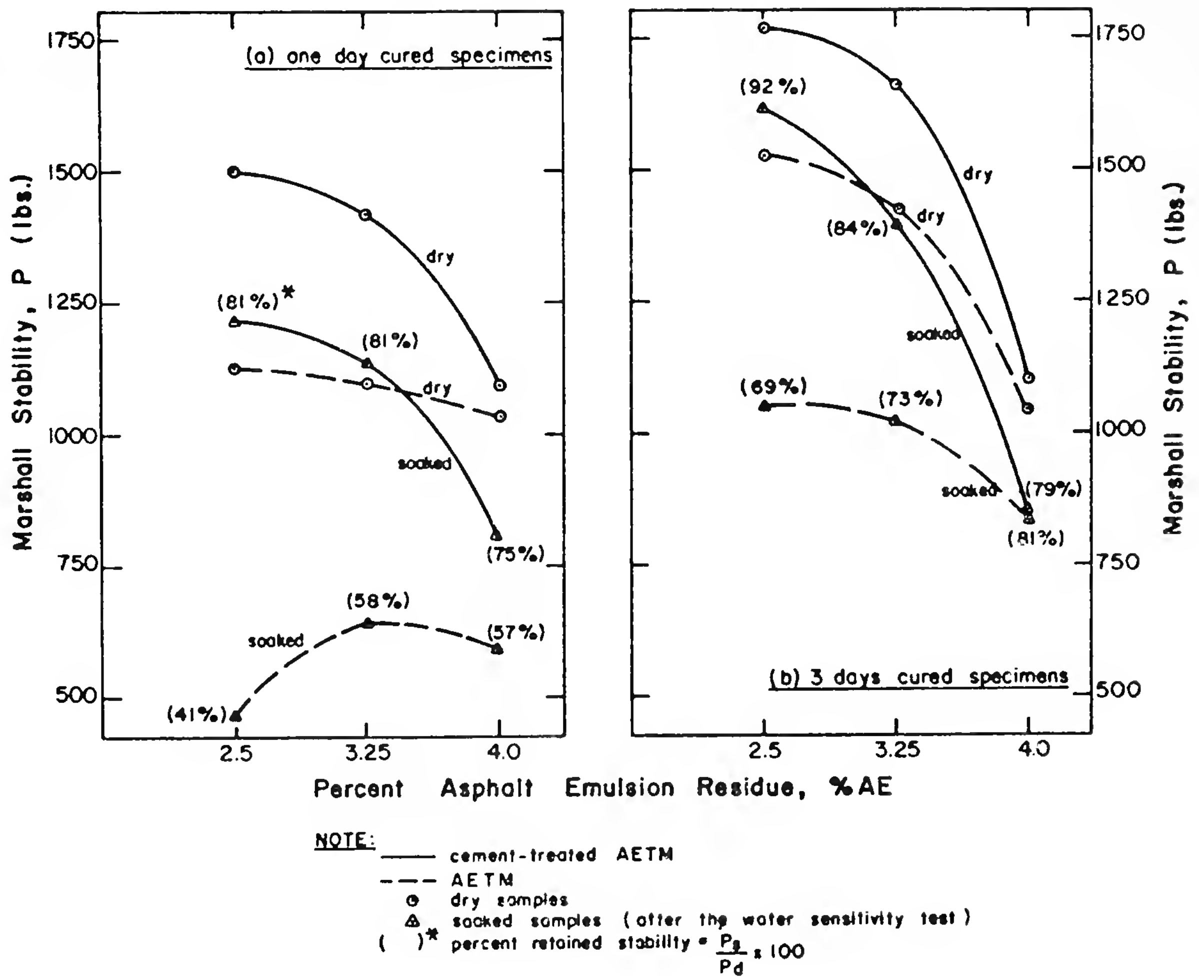


FIGURE 70, DRY AND SOAKED MARSHALL STABILITY FOR AETM AND CEMENT-TREATED AETM (MG aggregate, 3% added moisture)

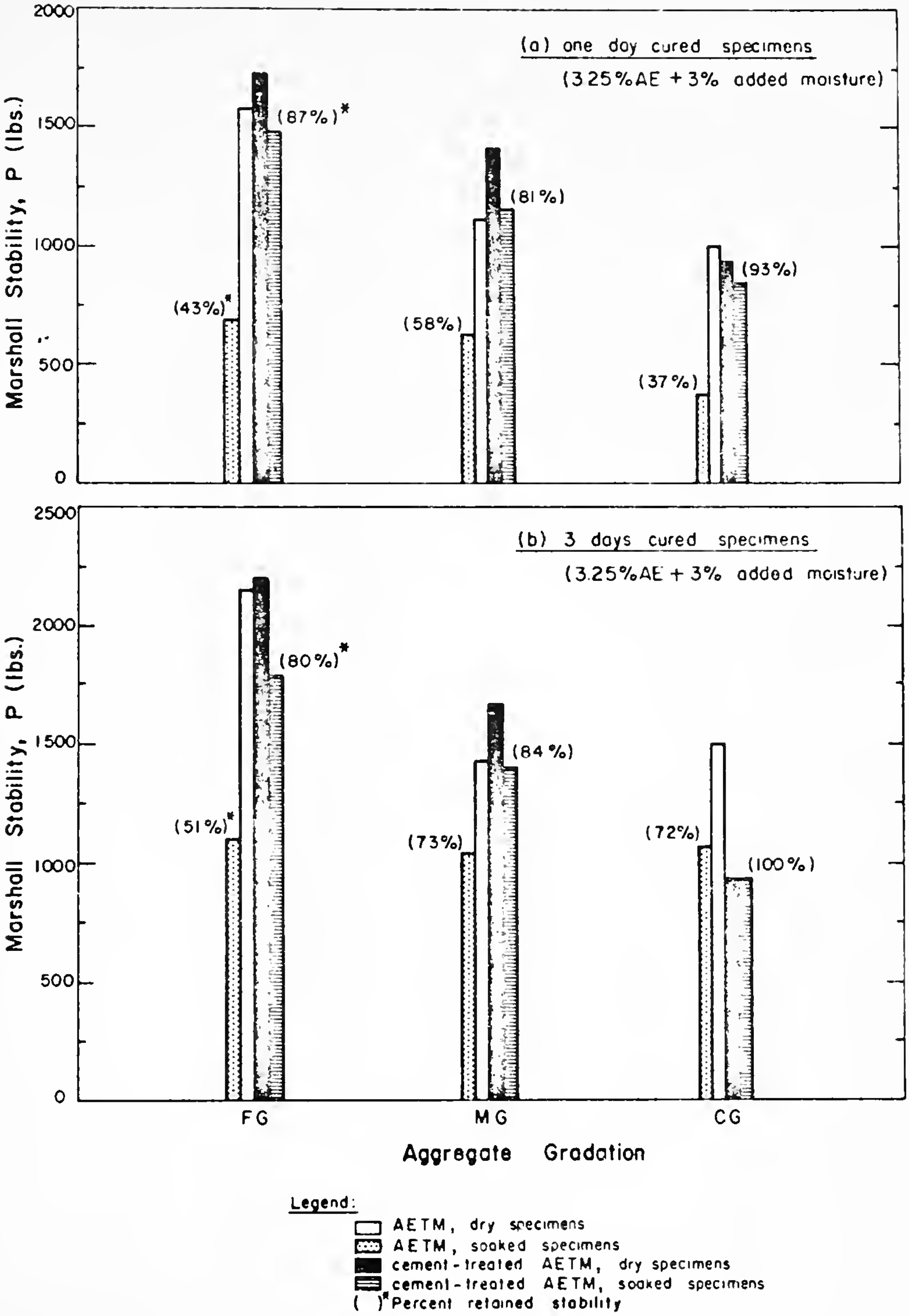


FIGURE 71, EFFECT OF PORTLAND-CEMENT ON MARSHALL STABILITY (P) FOR THE DIFFERENT AGGREGATE GRADATIONS

water sensitivity tests in evaluating the AETM performance and that the use of the dry test results alone is not sufficient for understanding and controlling the AETM performance.

Percent Retained Marshall Stiffness, $\%S_m$

The cement-treated AETM showed higher retained Marshall Stiffness values when subjected to the water action than the AETM. This can be seen in Figure 72, in which $\%S_m$ represents the ratio between (S_m) after the water sensitivity test and (S_m) for the dry samples, in percent.

Effect of Added Moisture Content on the Role of Portland-Cement

To examine the effect of added moisture content (%W) on the role of portland-cement in AETM, test results were examined for the limited tests that were run on cement-treated AETM (MG aggregate, and 1.5% added moisture) at two curing periods; 7 days air-dry curing and the ultimate curing condition (see Table 3). The effect of P.C. on the AETM properties was more apparent for samples with 1.5% added moisture as compared to samples with 3%W. Figures 73 and 74 present the Marshall stability and stiffness results for the two %W under study. In these figures the effect of P.C. is more pronounced for samples with less added moisture (1.5% vs. 3.0%) which indicates that %W affects the action of P.C. in the AETM system. These two parameters were presented here as an example. The other parameters were slightly affected but not with the same magnitude as P, S_m, and I_m. All the reduced data are presented in Table E2 in the appendices. It has to be noticed that this portion of the tests was limited and was not intended to provide a detailed evaluation of this factor.

Summary of Results

The main purpose of this phase of the study was to evaluate the interaction effect between portland-cement additive, aggregate gradation, and asphalt emulsion content on the AETM properties at different curing periods. The use of P.C. as an additive to the AETM has proved to be

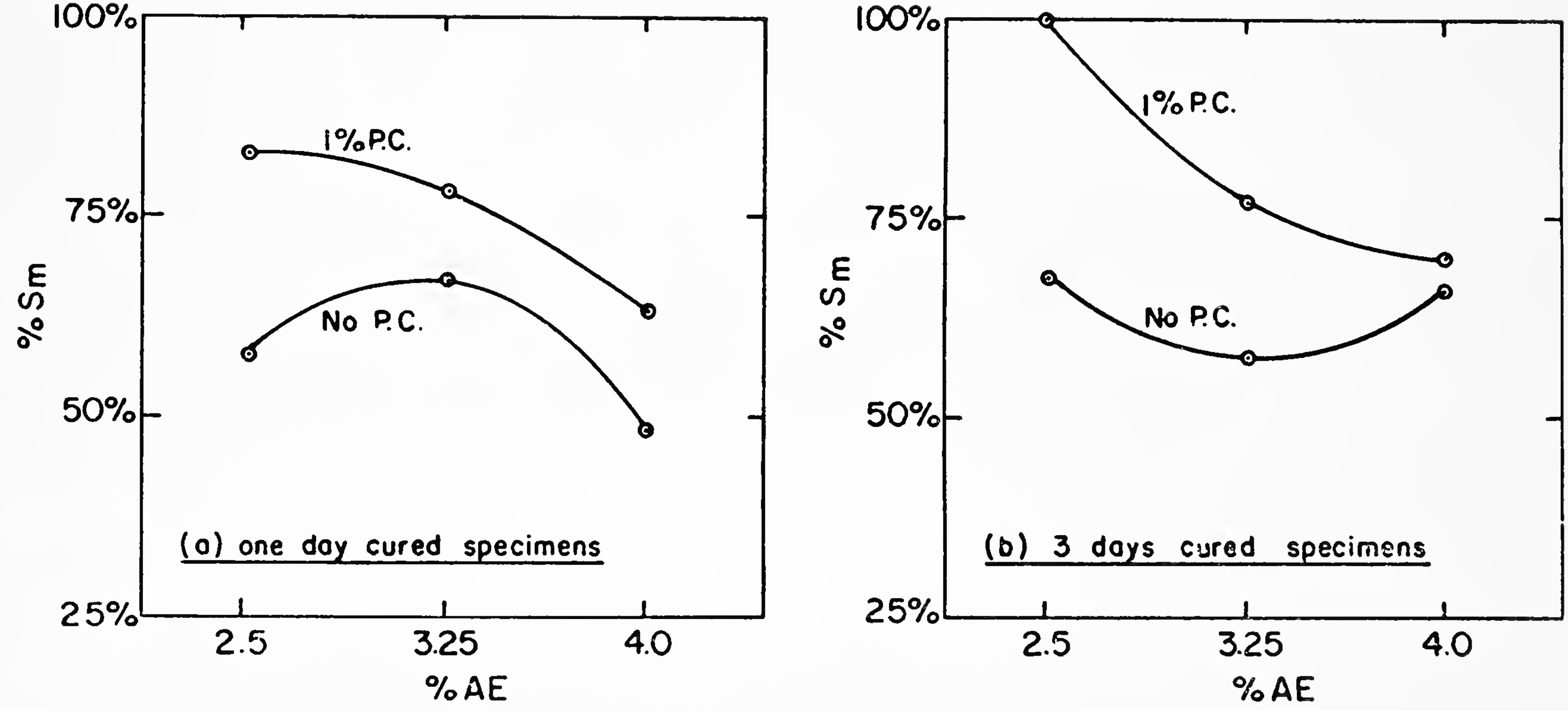


FIGURE 72, PERCENT RETAINED MARSHALL STIFFNESS (% S_m) FOR AETM AND CEMENT-TREATED AETM (MG aggregate, 3% added moisture)

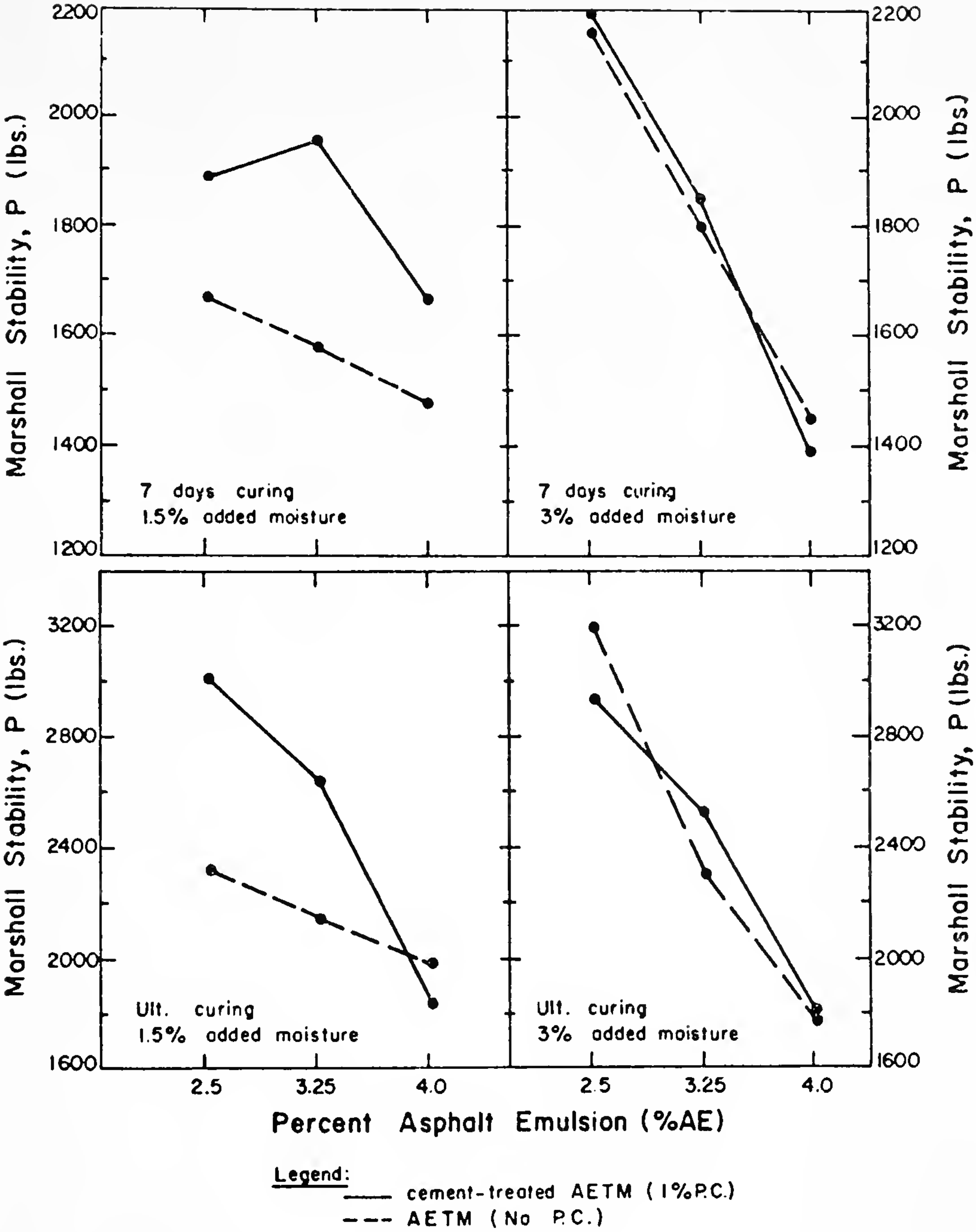


FIGURE 73, INFLUENCE OF ADDED MOISTURE CONTENT ON THE ROLE OF PORTLAND-CEMENT (MG aggregate)

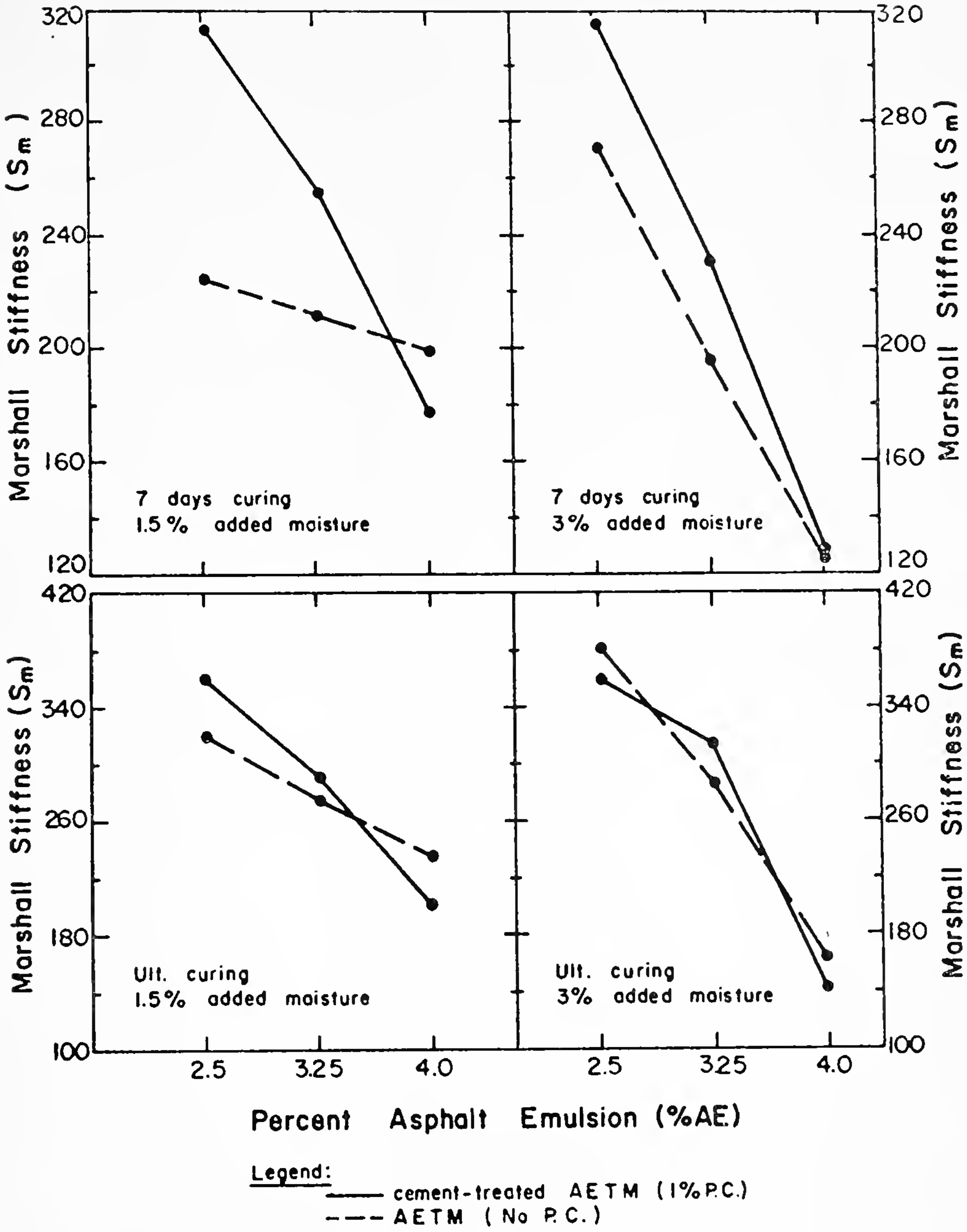


FIGURE 74, INFLUENCE OF ADDED MOISTURE CONTENT ON THE ROLE OF PORTLAND-CEMENT (MG aggregate)

beneficial in improving its properties. However, this result has to be viewed with caution due to the finding that the role of P.C. on AETM performance was significantly influenced by the aggregate gradation, asphalt emulsion content, and curing stage. The results reported in this chapter pertain to AETM that contained 3% added moisture. Following are the significant findings.

1. AETM showed less coating when treated with 1% portland cement. The cement-treated AETM appeared drier than the AETM during the testing.
2. Cement-treated AETM resulted in more retained moisture ($\%WC_0$) than the AETM specimens. However, a portion of this moisture has combined with the portland cement.
3. In general, AETM specimens possessed higher γ_d than the cement treated specimens, however, the interaction effects between P.C. and curing, and %AE were significant which necessitates the study of each case separately.
4. (a) The effect of portland cement on stability values was influenced by aggregate gradation, and %AE. At low %AE, the use of P.C. was beneficial in increasing the Marshall stability values for all aggregate gradations used. However, by increasing %AE in the mix the role of P.C. was affected by the aggregate gradation. The use of portland-cement with CG aggregate mixes was not beneficial and in some cases it resulted in a reduction in stability. This could be attributed to the poor coating that was observed for CG aggregate when treated with P.C.

   (b) The effect of P.C. on stability was more apparent at the early curing condition.

   (c) In spite of the increase in %TL due to the use of P.C., the "stability-%TL" trends showed a significant gain and increase in stability when AETM were treated with P.C. (note that this was also dependent on the aggregate gradation).

   (d) From a limited study; the added moisture content affected the role of P.C. in the AETM. The use of 1.5% added moisture signified the effect of P.C. in increasing the stability values as compared to 3% added moisture specimens.

5. The flow values (F), were not significantly affected by the use of portland-cement. From the results of the different phases of the study, it is the opinion of the author that the F values alone are the least significant parameter that explains the AETM performance.
6. The effect of P.C. on the air voids was dependent mainly on the aggregate gradation and %AE used. However, the total voids (%V_T) increased in general due to the use of portland cement.
7. P.C. significantly increased I_m values, however, the S_m values were not significantly affected by the use of P.C. due to the fact that S_m is dependent on P, and F. Flow values were not significantly affected by P.C. and the change in F due to the use of P.C. varied and consequently reduced the effect of P.C. on S_m values.
8. The use of P.C. improved the AETM properties and its resistance to water damage. The effect of P.C. was more beneficial and apparent for mixes with low %AE. The P.C. effect on the AETM resistance to water damage was of value especially at early curing condition. All aggregate gradations (FG, MG, and CG) benefitted from the use of P.C. and improved their resistance to water damage especially the CG aggregate mixes.

CHAPTER X: CONCLUSIONS AND RECOMMENDATIONS

A detailed evaluation of the properties and performance of AETM has been presented in this investigation. Different aggregate gradations, asphalt emulsion residue contents, different curing periods and added moisture contents were utilized in the study. In addition, the effect of using 1% portland-cement as an additive to the AETM has been evaluated. A modified Marshall method for preparing and testing AETM specimens was developed and used in the evaluation section of the study.

The evaluation of AETM properties resulted in a number of significant results. It must be recognized that the properties of AETM are an outcome of a complex array of factors. Evaluating the mix properties as related to only a single factor is not sufficient. The interaction of these factors influence the behavior and properties of the AETM and have to be considered in the evaluation. It must be emphasized that the conclusions pertain to the materials and testing procedures used in this study. Justifiable extrapolation of the results should be made only after further testing. The following is a brief summary of the significant findings of the study.

1. The percent moisture retained in the sample ($\%WC_0$) is a function of asphalt emulsion content, added moisture content, aggregate gradation, and curing time; with the added moisture content (%W) having a greater bearing on $\%WC_0$ especially at the early curing condition.
2. The use of portland-cement resulted in an increase in percent moisture retained. However, a portion of this moisture has combined with the portland cement.
3. Both asphalt emulsion content (%AE) and added moisture content (%W) and their interaction significantly affected the dry and wet unit weights of AETM. The optimum total liquid that provided a maximum dry density was lower than that required to provide a maximum wet density.

4. In general, AETM specimens possessed higher dry unit weights than the cement-treated specimens, however, the interaction effects between portland-cement, curing, and asphalt-emulsion content were significant which necessitate study each case separately.
5. The effect of percent asphalt emulsion on Marshall Stability was not significantly apparent at early curing condition. However, the asphalt emulsion content significantly affected the Marshall Stability when the samples were allowed to cure for longer periods of time.
6. The effect of portland-cement on stability values was dependent on aggregate gradation, and percent asphalt emulsion (%AE). At low %AE, the use of Portland Cement was beneficial in increasing the Marshall stability values for all aggregate gradations used. However, at increasing %AE in the mix the aggregate gradation affected the contribution of the portland cement.
7. The Marshall Flow (F) values were significantly affected by the aggregate gradation, asphalt emulsion content, added moisture content, and curing time. However, they were not significantly affected by the use of Portland-cement. Also, it was evident from the study that the F values alone are the least significant parameter that explains the AETM performance.
8. Air voids and total voids in the AETM are directly related to the curing time, asphalt emulsion content, and percent added moisture. The air-voids increased with decreasing percent total liquid as a result of extending the curing period. However, the percent total voids, for a specific mix, was about the same through the curing process.
9. The effect of portland cement on the air voids was dependent mainly on the aggregate gradation and %AE used. However, the total voids increased in general due to the use of portland-cement.

10. The Marshall stiffness (S_m) and Index (I_m) parameters show a unique trend that depend on the percent total liquid, asphalt emulsion content, and amount of added moisture (for a specific aggregate type and gradation). S_m and I_m values decreased with increasing the percent of total liquid at time of testing. While the stability values were not sensitive to changes in percent asphalt emulsion at early curing condition, the stiffness parameters showed a significant response to changing the percent asphalt emulsion residue.
11. The AETM stiffness indices S_m and I_m increased through the curing process. However, this gain in stiffness was dependent mainly on the asphalt emulsion content in the mix.
12. The S_m and I_m values were not significantly affected by changing percent added moisture from 1.5% to 3.0%.
13. Portland cement significantly increased I_m values, however, the S_m values were not significantly affected by the use of portland cement.
14. Marshall Stiffness and/or Index could be used, in addition to the conventional design parameters for Marshall method of mix design, to better control the mix properties by setting minimum values for these two parameters.
15. A linear first-order regression model was the most appropriate mean for representing the relationship between Marshall Index (I_m) and Marshall Stiffness (S_m), [see Appendix D].
16. Aggregate gradation significantly affected all the AETM properties. It should be noted that the three aggregate gradations fall within a certain specified gradation limits. This draws attention to the importance of controlling the aggregate gradation in the mix.
17. The test results for the unsoaked ("dry") specimens showed that the Marshall Stability increases with decreasing percent asphalt emulsion in the mix. However, mixes with low %AE showed the least resistance to water damage. The shape of the "stability vs. asphalt emulsion content" relationship for soaked specimens was different from that obtained for "dry" samples. This

difference was more pronounced when the samples were allowed to cure for extended periods of time.

18. The percent retained stability for any mix combination increased through the curing process.
19. The nature of the presence of water in the mix (drying through curing vs. soaking) affects the response parameters of the AETM.
20. The use of portland cement (P.C.) improved the AETM properties and its resistance to water damage. The effect of P.C. was more beneficial and apparent for mixes with low %AE. The P.C. effect on the AETM resistance to water damage was beneficial especially at the early curing condition. All aggregate gradations benefitted from the use of P.C. and improved their resistance to water damage.
21. The water sensitivity tests have to be an integral part of the Marshall Design Procedure for AETM. Generally, high stability is obtained at the expense of lowered durability (measured here as the resistance to water damage) especially when using the unsoaked ("dry") Marshall stability trends in the design of AETM. The final design must provide a balance between stability and durability requirements. This would be achieved by controlling and evaluating both the "dry" and soaked properties of the mix with a greater emphasis on the soaked specimen results.

Based on the results of the overall investigation and using the method of specimen preparation and testing as developed in the study, the following recommendations are in order.

1. Percent added moisture has to be evaluated based on two factors: Coating of aggregate and AETM response variables (properties). Bearing in mind that the different response variables (dry unit weight, wet unit weight, Marshall Stability,....) require different optimum percent total liquid (and consequently different combinations of asphalt emulsion and added moisture contents) to provide maximum values.
2. Percent asphalt emulsion residue (%AE) has to be evaluated in conjunction with percent added moisture (%W) in the AETM.

3. As a preliminary guide; a 2 x 3 factorial experiment (2 levels of %W and 3 levels of %AE) would be adequate for the design of AETM.
4. Evaluating the AETM properties at two different curing periods would provide a better understanding and control of the mix performance. The two curing periods have to be selected to represent the early curing condition and curing for a relatively long periods; with emphasis on the AETM properties at the early curing condition.
5. The water sensitivity test has to be the main part of the evaluation system. More reliance and use of the water sensitivity test results (soaked specimens) as compared to dry test results would be beneficial in providing realistic results and better control of the AETM properties.

CHAPTER XI: RECOMMENDATIONS FOR FURTHER RESEARCH

1. This study was limited to sand and gravel aggregate. The influence of aggregate type (e.g. sand and gravel vs. limestone) on AETM properties should be evaluated.
2. The results of this project have been based on laboratory testing of AETM using the Marshall Equipment. The findings of this study have to be further examined through a field study. This would provide a mean for setting adequate mix design criteria to be used with the AETM.
3. In this investigation, two of the measured output (response) parameters were Marshall Index (I_m) and Stiffness (S_m), based on the premise that they are more indicative of the AETM properties and performance. However, a need exists to study and evaluate these two parameters as related to some of the conventional mix properties such as the diametrial resilient modulus. The diametrial resilient modulus could be determined using some conventional means of cyclic loading as outlined and used by Chevron research company or through the use of an MTS electrohydraulic closed loop testing machine which is available in the Joint Highway Research Project Bituminous Laboratory at Purdue University. A study should be initiated to evaluate the relationship between the diametrial resilient modulus of the mix and Marshall test parameters, especially Marshall Stiffness and/or Marshall Index for both the unsoaked ("dry") and soaked conditions. This would provide an important tool for designing the AETM and a method for evaluating the structural capacity of the AETM layer in the pavement system.

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APPENDICES

APPENDIX A

SELECTION OF THE ASPHALT EMULSION CONTENT LEVELS TO BE USED IN THE EVALUATION STUDY

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SELECTION OF THE ASPHALT EMULSION CONTENT LEVELS TO BE USED IN THE EVALUATION STUDY

A preliminary study was conducted to define a general trend for the effect of asphalt emulsion residue content (%AE) on the mix response values. The purpose of this limited experiment was to select three levels of the independent factor (%AE) that would be incorporated in the evaluation part of the study.

A series of test specimens were prepared for a range of different asphalt emulsion residue contents from 2.5% to 4.5% (by weight of the dry aggregate). This range of %AE residue was chosen in accordance with ISHC specifications.* The other components of the AETM specimens were a MG aggregate and 3% initial added moisture content. In addition, all tests were conducted on AETM specimens that were cured for one day at room temperature.

Figures A1, and A2 show the mix properties after one day curing at room temperature as a function of the asphalt emulsion content.

The dry density values (γ_d) ranged from 144.6 pcf to 145.3 pcf with an optimum %AE of about 4.0% and percent total liquid, %TL, of about 5.65% (This represents the total amount of liquid available at time of testing which includes the asphalt emulsion residue and the retained moisture). "The wet density (γ_w)-%AE" relationship followed the same trend as γ_d. A study of the percent air voids and total voids, shows a decrease in their values with increasing %AE residue.

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*ISHC specifications call for 2.5% and 4.5% as minimum and maximum limiting values for the %AE residue in the mixture (expressed as percent by weight of the total mixture exclusive of water or solvent). These limiting values are about 2.6% to 4.7% by weight of the dry aggregate. (See articles 404.02, p. 168, and 406.07, p. 175 in ISHC specifications (32)).

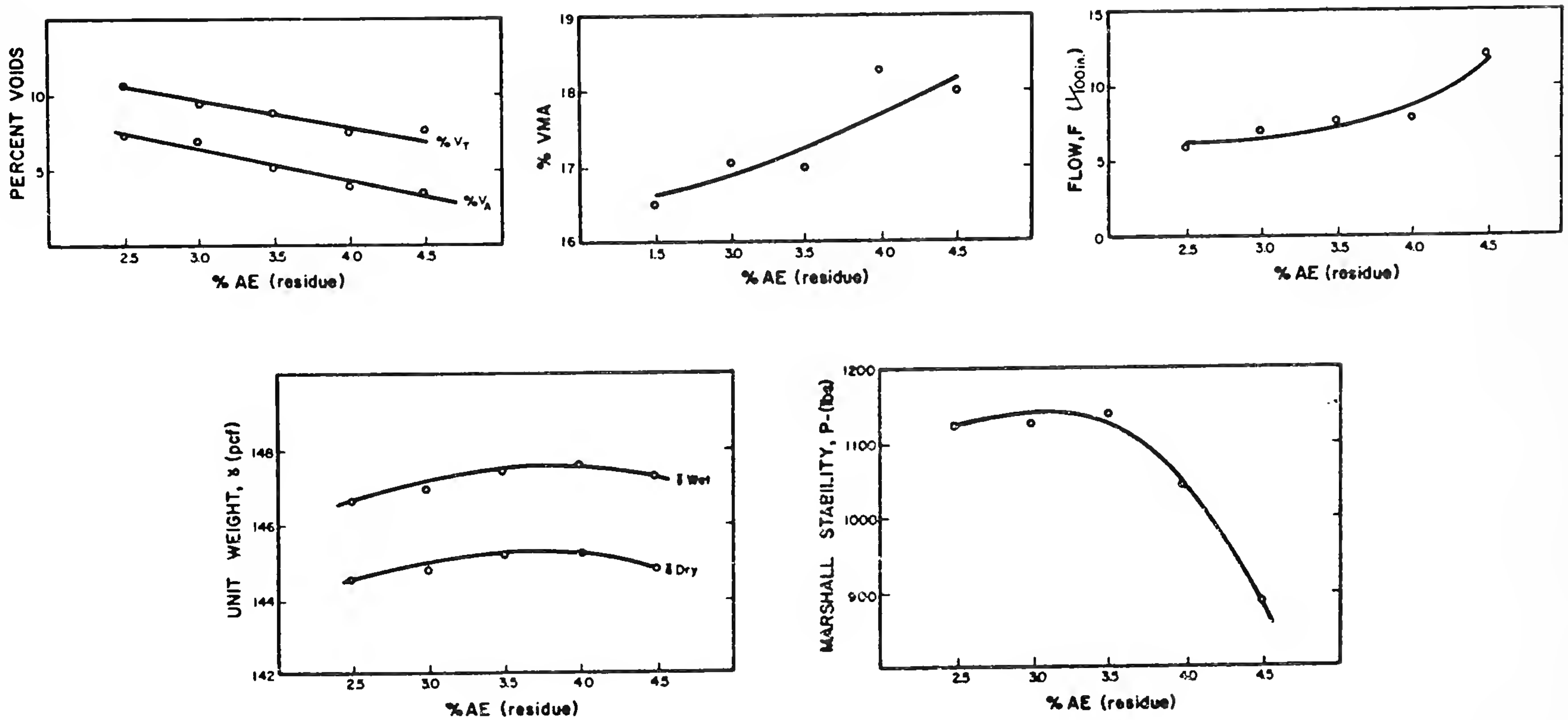


FIGURE A1, MIXTURE PROPERTIES (MG GRADATION, 3% INITIAL MOISTURE CONTENT, AND ONE DAY CURRING AT ROOM TEMPERATURE)

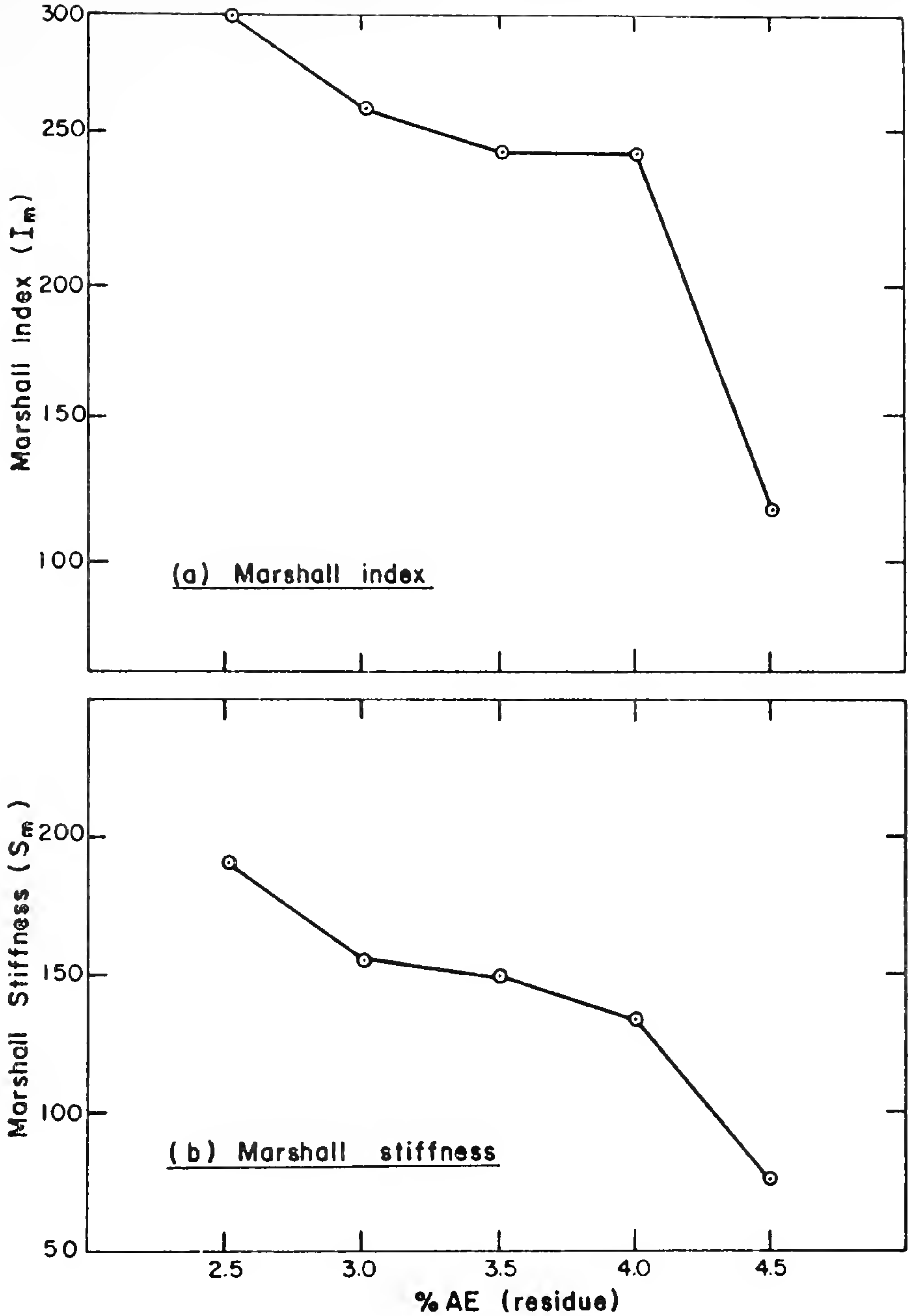


FIGURE A2, EFFECT OF ASPHALT EMULSION CONTENT ON THE MARSHALL STIFFNESS AND INDEX (MG aggregate, 3% added moisture, one day cured specimens)

The Marshall stability values (P) were about the same for low and medium asphalt emulsion contents. This was followed by a drop in stability values when using a high asphalt emulsion contents. The apparent optimum %AE that provided a maximum stability value was in the range between 3.0 and 3.5%. In addition, the Marshall stiffness and Index values followed a specific trend and decreased with increasing the asphalt emulsion content (Figure A2).

From this preliminary study the three levels of %AE residue were selected as follows: one level (2.5% AE residue) on the dry side of the P vs %AE relationship to provide an adequate information about the properties of the AETM that contain small amounts of the asphalt emulsion. The second level was selected around the optimum %AE (3.25% AE residue). The third one was chosen on the wet side of the P vs %AE relationship (4.0% AE residue). It has to be noticed that the three asphalt emulsion residue contents are equally spaced within the selected range of 2.5-4%.

Appendix B

Typical ANOVA Tables

TABLE B1, Summary of Analysis of Variance of Marshall Stability (P), (Phase 1)

Source of variation		DF	Mean Square	Expected Mean Square	F	Significance
%AE ,	(A_i)	2	23004.9	$\sigma_\varepsilon^2 + 12\ \phi(A)$	2.07	N.S.
%W ,	(w_j)	3	206856.5	$\sigma_\varepsilon^2 + 9\ \phi(W)$	18.59	S^*
	(AW_{ij})	6	24661.3	$\sigma_\varepsilon^2 + 3\ \phi(AW)$	2.22	S^{**}
error,	$\varepsilon_{(ij)k}$	24	11126.4	σ_ε^2		

S^* = significant at $\alpha = 0.05$

S^{**} = significant at $\alpha = 0.10$

NS = not significant at $\alpha = 0.10$

σ^2 = variance

ϕ = fixed component of the factor or interaction

TABLE B2, Summary of Analysis of Variance of Marshall Stability(P), (Phase 2, design 1)

Source of variation		DF	Mean Square	Expected Mean Square	F	Significance
Curing time,	(C_i)	4	4151339.9	$\sigma_\varepsilon^2 + 18\,{}_\delta^2 + 18\phi(C)$	277.47	**
restriction error,	$(\delta_{(i)})$	0	------	$\sigma_\varepsilon^2 + 18\sigma_\delta^2$	----	--
%AE ,	(A_j)	2	921841.1	$\sigma_\varepsilon^2 + 30\phi(A)$	61.61	S^*
%W ,	(W_K)	1	1094506.1	$\sigma_\varepsilon^2 + 45\phi(W)$	73.15	S^*
(CA_{ij})		8	172245.3	$\sigma_\varepsilon^2 + 6\phi(CA)$	11.51	S^*
(CW_{iK})		4	28192.4	$\sigma_\varepsilon^2 + 9\phi(CW)$	1.88	N.S.
(AW_{jK})		2	385854.4	$\sigma_\varepsilon^2 + 15\phi(AW)$	25.79	S^*
(CAW_{ijK})		8	86625.3	$\sigma_\varepsilon^2 + 9\phi(CAW)$	5.79	S^*
error,	$\varepsilon_{(ijK)\ell}$	60	14961.7	σ_ε^2		

S^* = significant at $\alpha = 0.05$

N.S. = not significant at $\alpha = 0.05$

** = indirect test, see discussion on p. 74. (significant at $\alpha = 0.001$)

TABLE B3. Summary of Analysis of Variance of Marshall Stability (P), (Phase 2, design 2)

Source of Variation	DF	Mean Square	Expected Mean Square	F	Significance
curing time, (C_i)	1	12053392.6	$\sigma_\varepsilon^2 + 54\sigma_\delta^2 + \phi(C)$	---	------
restriction error, $(\delta_{(i)})$	0	-------	$\sigma_\varepsilon^2 + 54\sigma_\delta^2$	---	------
Gradation, (G_j)	2	3953979.4	$\sigma_\varepsilon^2 + 36\phi(G)$	295.43	S
%AE, (A_K)	2	644273.8	$\sigma_\varepsilon^2 + 36\phi(A)$	48.14	S
%W, (W_ℓ)	1	819889.8	$\sigma_\varepsilon^2 + 54\phi(W)$	61.26	S
(CG_{ij})	2	7146.1	$\sigma_\varepsilon^2 + 18\phi(CG)$	.53	N.S.
(CA_{iK})	2	352140.5	$\sigma_\varepsilon^2 + 18\phi(CA)$	26.31	S
$(CW_{i\ell})$	1	403333.3	$\sigma_\varepsilon^2 + 27\phi(CW)$	30.14	S
(GA_{jK})	4	62526.6	$\sigma_\varepsilon^2 + 12\phi(GA)$	4.67	S
$(GW_{j\ell})$	2	80503.0	$\sigma_\varepsilon^2 + 18\phi(GW)$	6.01	S
$(AW_{K\ell})$	2	188886.3	$\sigma_\varepsilon^2 + 18\phi(AW)$	14.11	S
(CGA_{ijK})	4	8512.7	$\sigma_\varepsilon^2 + 6\phi(CGA)$	.64	N.S.
$(CGW_{ij\ell})$	2	65352.1	$\sigma_\varepsilon^2 + 9\phi(CGW)$	4.88	S
$(CAW_{iK\ell})$	2	237104.9	$\sigma_\varepsilon^2 + 9\phi(CAW)$	17.72	S
$(GAW_{jK\ell})$	4	11822.5	$\sigma_\varepsilon^2 + 6\phi(GAW)$	.88	N.S.
$(CGAW_{ijK\ell})$	4	36521.5	$\sigma_3^2 + 3\phi(CGAW)$	2.73	S
error, $\varepsilon_{(ijK\ell)m}$	72	13383.8	σ_ε		

S = significant at $\alpha = 0.05$
N.S. = not significant at $\alpha = 0.05$

TABLE B4, Expected Mean Square for Analysis of Variance of AETM Properties (Phase 2, Design 3)

Source	Degrees of Freedom	Expected Mean Square
O_i	1	$\sigma_\varepsilon^2 + 27\sigma_\delta^2 + 108\phi(O)$
C_j	3	$\sigma_\varepsilon^2 + 27\sigma_\delta^2 + 54\phi(C)$
OC_{ij}	3	$\sigma_\varepsilon^2 + 27\sigma_\delta^2 + 27\phi(OC)$
$\delta_{(ij)}$	0	$\sigma_\varepsilon^2 + 27\sigma_\delta^2$
G_K	2	$\sigma_\varepsilon^2 + 72\phi(G)$
A	2	$\sigma_\varepsilon^2 + 72\phi(A)$
OG_{iK}	2	$\sigma_\varepsilon^2 + 36\phi(OG)$
CG_{jK}	6	$\sigma_\varepsilon^2 + 18\phi(CG)$
OA_i	2	$\sigma_\varepsilon^2 + 36\phi(OA)$
CA_j	6	$\sigma_\varepsilon^2 + 18\phi(CA)$
GA_K	4	$\sigma_\varepsilon^2 + 24\phi(GA)$
OCG_{ijK}	6	$\sigma_\varepsilon^2 + 9\phi(OCG)$
$OCA_{ij\ell}$	6	$\sigma_\varepsilon^2 + 9\phi(OCA)$
$OGA_{iK\ell}$	4	$\sigma_\varepsilon^2 + 12\phi(OGA)$
$CGA_{jK\ell}$	12	$\sigma_\varepsilon^2 + 6\phi(CGA)$
$OCGA_{ijK\ell}$	12	$\sigma_\varepsilon^2 + 3\phi(OCGA)$
$\varepsilon_{(ijK\ell)m}$	144	σ_ε^2
Total	215	

σ^2 = variance

ϕ = fixed component of the factor or interaction

TABLE B5, Summary of Analysis of Variance of Marshall Stability (P), (Phase 2, Design 3)

Source Variation	DF	Mean Squeares	F	Significance
Portland Cement,, (O_i)	1	125426.0	---	-----
Curing time, (C_j)	3	19707527.3	---	-----
(OC_{ij})	3	65587.2	---	-----
$\delta_{(ij)}$	0	----	---	-----
aggregate gradation,(G_K)	2	13731281.0	726.98	S
%AE, (A_ℓ)	2	8639968.5	457.43	S
(OG_{iK})	2	150754.2	7.98	S
(CG_{jK})	6	236554.0	12.52	S
$(OA_{i\ell})$	2	82172.2	4.35	S
$(CA_{j\ell})$	6	773262.4	40.94	S
$(GA_{K\ell})$	4	12917.3	.68	N.S.
(OCG_{ijK})	6	32426.9	1.72	N.S.
$(OCA_{ij\ell})$	6	23857.4	1.26	N.S.
$(OGA_{iK\ell})$	4	59225.9	3.14	S
$(CGA_{jK\ell})$	12	62781.3	3.32	S
$(OCGA_{ijK\ell})$	12	63009.4	3.34	S
$\epsilon_{(ijK\ell)m}$	144	18888.2		

S = significant at α = 0.05 N.S. = not significant at α = 0.05

TABLE B6, Summary of Analysis of Variance of Marshall Index (I_m), (Phase 2, Design 3)

Source of Variation	DF	Mean Squares	F	Significance
Portland Cement, (O_i)	1	108093.6	68.38	S^+
Curing time, (C_j)	3	304963.0	192.92	S^+
(OC_{ij})	3	1051.3	.67	N.S.$^+$
$\delta_{(ij)}$	0	-----	---	-----
aggregate gradation, (G_K)	2	765111.5	484.02	S
%AE, (A_ℓ)	2	801792.1	507.22	S
(OG_{iK})	2	10161.4	6.43	S
(CG_{jK})	6	14899.2	9.43	S
$(OA_{i\ell})$	2	2635.9	1.67	N.S.
$(CA_{j\ell})$	6	45620.0	28.86	S
$(GA_{K\ell})$	4	7753.4	4.91	S
(OCG_{ijK})	6	9863.2	6.24	S
$(OCA_{ij\ell})$	6	4929.6	3.12	S
$(OGA_{jK\ell})$	4	20000.2	12.65	S
$(CGA_{jK\ell})$	12	1865.4	1.18	N.S.
$(OCGA_{ijK\ell})$	12	2971.5	1.88	S
$\epsilon_{(ijK\ell)m}$	144	1580.8		

S = significant at $\alpha = 0.05$

N.S. = not significant at $\alpha = 0.05$

+ = indirect test, see siscussion on p. 128.

Appendix C

Development of Marshall Index (I_m) Prediction Model

Appendix C

Development of Marshall Index (I_m) Prediction Model

The two new parameters that were used in the study to evaluate the AETM properties are the Marshall Stiffness (S_m) and Marshall Index (I_m). As was pointed out earlier, each one of these two parameters provide a measure of the AETM characteristics at a specific condition. The Marshall Stiffness (S_m) provides a measure of the AETM properties at the failure condition and its determination is based on the deterministic equation: $S_m = P/F$; that is, S_m is directly related and measured as a function of the standard Marshall Stability (P) and Flow (F).

On the other hand, the Marshall Index (I_m) provides a measure of the AETM characteristics during the loading duration and determined as the slope of the linear portion of the load-deformation trace obtained from the autographic Marshall Equipment. However, in case that the autographic Marshall Equipment is not available and due to the peculiarity of the standard Marshall test, an estimate of this "strength" parameter is not available. Therefore, a statistical approach was used to provide a prediction model for the estimation of Marshall Index (I_m) as a function of the two standard Marshall Indices P, and F and accounting for the different independent factors that were considered in the study.

Linear regression analysis models (2,15) were hypothesized to study the relationship between the dependent variable: Marshall Index (I_m) and the independent variables: additives, curing time, aggregate gradation, asphalt emulsion content, added moisture content, Marshall stability, and Marshall Flow. All data points (306 individual measurements) were utilized in the regression analysis. The different models from the regression analysis of the test data were examined (2,15) and the one providing the best fit of the data was selected. It has to be mentioned that after examining the different linear regression models, the curing

time factor was not included in the selected prediction model due to its non significant contribution to the regression model.

The resulting prodiction model is:

$$I_m = 365.910 + 35.771\,(P.C.) - 35.364(A) + 14.676(G) - 22.295(W) + 0.159(P) - 17.727(F)$$

where

I_m = Marshall Index (lbs./0.01" units)

P.C. = portland cement factor = 0 (no P.C. used) or = 1 (1% P.C. used)

A = %AE residue = 2.5, 3.25 or 4.0

G = aggregate gradation = 4 (for FG aggregate) or = 2 (for MG aggregate) or = 1 (for CG aggregate)

W = %W = 1.5, or 3.0

P = Marshall Stability (in lbs.)

F = Marshall Flow (in 0.01" units)

The aggregate gradation term (G) was assigned the values of 4, 2, or 1 to represent the three different aggregate gradations FG, MG, or CG, respectively. The selection of these values was based on the actual spacing between the grain size distribution of the three aggregate gradations.

The coefficient of determination (R^2) for the prediction model is 0.914 and the standard error of estimate is 41.96.

One should be cautioned that the prediction model is limited in applicability to the material and testing procedure that were used in the study. The statistical attributes of the prediction model are presented in table C1.

TABLE C1, Statistical Attributes of the Regression Equation for the Marshall Index (I_m)

. Dependent variable, I_m = estimated Marshall Index

. Mean response = 378.2

. Standard error of estimate, (S_E) = 41.96

. Coefficient of determination, (R^2) = 0.914

. No. of cases. 306

Independent Variable	Variable Description	Regression Coefficient	Standard Error	F^*
Constant	---------	365.910	18.614	-------
P.C.	portland cement	35.771	5.155	48.15**
A	%AE residue	-35.364	4.970	50.62**
G	aggregate gradation	14.676	2.510	34.18**
W	%W	-22.295	3.817	34.11**
P	Marshall Stability	0.159	.005	1220.79**
F	Marshall Flow	-17.727	1.546	131.50**

* F-test for significance of regression coefficient, with model containing all independent variables

** Significant at $\alpha = 0.01$

Appendix D

Relationahip Between Marshall Index (I_m) and Marshall Stiffness (S_m)

Appendix D

Relationship Between Marshall Index (I_m) and Marshall Stiffness (S_m)

The test results of the overall study for the unsoaked ("dry") specimens were utilized to determine the relationship between Marshall Index (I_m) and Marshall Stiffness (S_m).

Linear regression analysis models were hypothesized to study the relationship between the dependent variable: Marshall Index and the independent variable: Marshall Stiffness. All data points (342 individual measurements) of the overall study were utilized in the regression analysis. An examination of the results indicates that the two parameters have a linear relationship and that a linear first-order regression model is the most appropriate for representing the relationship between Marshall Index and Stiffness.

The resulting regression model is:

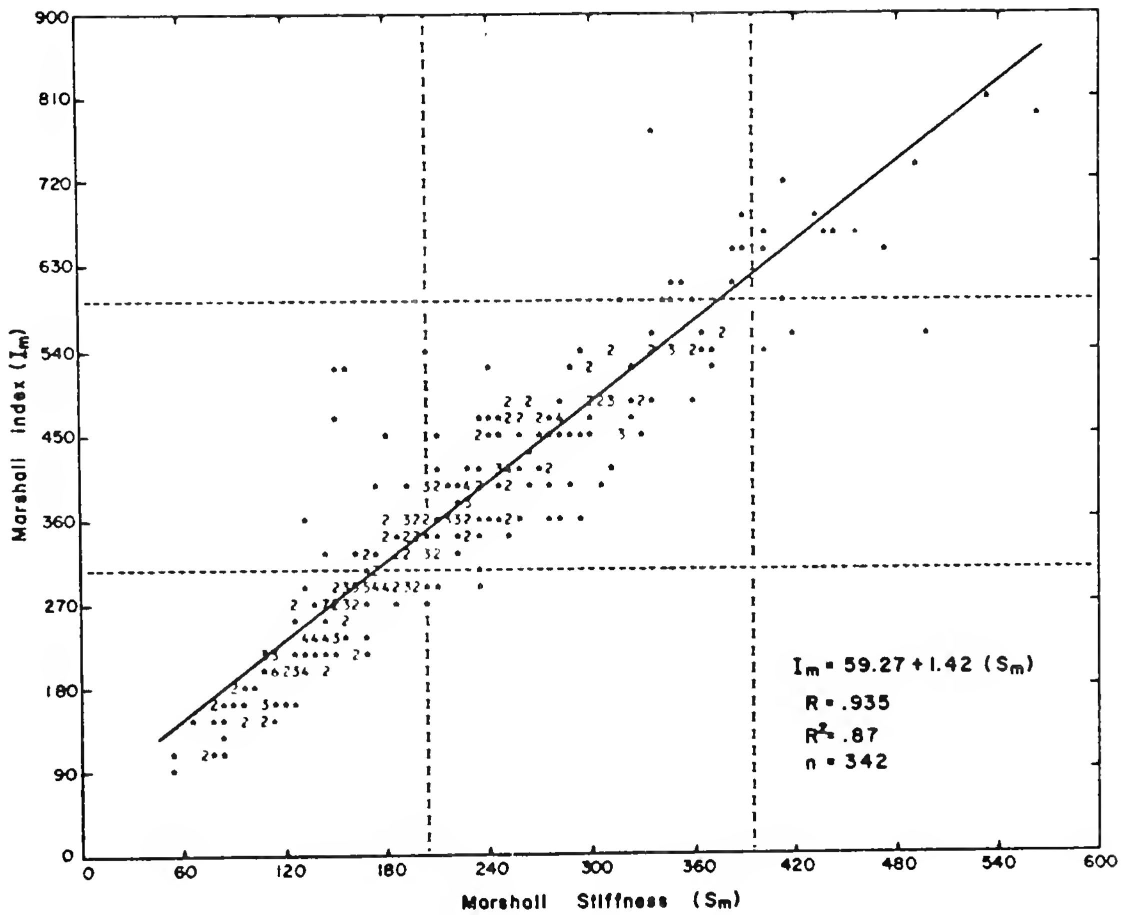
$$I_m = 59.27 + 1.42(S_m)$$

where

I_m = Marshall Index (lbs./0.01" units)

S_m = Marshall Stiffness (lbs./0.01" units)

The coefficient of determination (R^2) for the regression model is 0.87 and the standard error of estimate is 49.47. Figure D1 shows the relationship between I_m and S_m. All test data were plotted with the regression model obtained. Also, the statistical attributes of the regression model are presented in table D1.



NOTE: in the graph one occurrence is represented by an astrisk (*); two to seven by the numbers 2 through 7.

FIGURE D1, RELATIONSHIP BETWEEN MARSHALL INDEX (I_m) AND MARSHALL STIFFNESS (S_m)

TABLE D1, Statistical Attributes of the Regression Equation for the Marshall Index (I_m)

- Dependent variable, I_m = estimated Marshall Index
- Mean response = 368.9
- Standard error of estimate, (S_ε) = 49.47
- Coefficient of determination, (R^2) = 0.874
- No. of cases = 342

Independent Variables	Regression Coefficient	Standard Error	F^*
Constant	59.272	6.913	----
Marshall Stiffness (S_m)	1.420	.029	73.51^{**}

* F-test for significance of regression coefficient; with model containing all independent variables.

** Significant at $\alpha = 0.01$

Appendix E

Summary of AETM Testing Results

TABLE E1, Summary of AETM Testing Results

Notes:

(1) - The reduced data are the average of the three replicate specimens for each mix combination

(2) - All response parameters (measured properties) symbols are defined in the "list of symbols" at the beginning of the report.

(3) - Each data set is identified by an ID number (2nd column in the tables), which identifies the entire series of factors and conditions that correspond to the data set. The ID number consists of five numbers.

* The first number represent curing time; where
  1 = one day air-dry
  3 = 3 days air-dry
  5 = 5 days air-dry
  7 = 7 days air-dry
  9 = ultimate curing condition
* The 2nd number represent the use of portland cement; where
  1 = 1 %P.C. was used
  2 = No P.C. was used
* The 3rd number represent aggregate gradation; where
  1 = FG
  2 = MG
  3 = CG
* The 4th number represent the asphalt emulsion residue content (%AE); where
  2 = 2.5%
  3 = 3.25%
  4 = 4.0%
* The 5th number represent the added moisture content (%W); where
  0 = 0%
  1 = 1.5%
  3 = 3.0%
  4 = 4.0%

Therefore, the first data set corresponds to a mix combination having an ID number of 12121. It means that the mix was tested after one day air-dry curing, No P.C. was used, FG aggregate, 2.5% AE residue, and 1.5% added moisture was used, respectively.

TABLE EI, CONTD.

No.	ID	G_d	G_w	$\%WC_o$	%TL	$\%V_A$	$\%V_W$	$\%V_T$	VMA	P	F	S_m	I_m
1	12121	2.248	2.261	.62	3.12	11.8	1.4	13.2	18.8	1575.0	7.0	225.0	385.0
2	12131	2.280	2.311	1.41	4.66	7.8	3.1	10.9	18.2	1475.0	7.7	196.3	313.3
3	12141	2.308	2.343	1.58	5.58	5.3	3.5	8.8	17.8	1466.7	6.2	244.3	383.3
4	12123	2.280	2.311	1.39	3.89	8.8	3.1	11.9	17.6	1475.0	6.8	216.7	376.7
5	12133	2.283	2.316	1.50	4.75	7.5	3.3	10.8	18.1	1580.0	6.0	265.0	458.3
6	12143	2.327	2.360	1.50	5.50	5.4	3.4	8.8	17.1	1625.0	7.8	207.7	345.0
7	32123	2.273	2.292	1.05	3.55	10.1	2.3	12.4	18.0	2233.3	7.6	292.3	433.3
8	32133	2.304	2.333	1.29	4.54	7.0	2.9	9.9	17.3	2145.7	7.3	294.3	393.3
9	32143	2.287	2.320	1.49	5.49	6.3	3.3	9.6	18.5	1193.3	11.1	108.0	156.7
10	72121	2.249	2.261	.56	3.06	12.0	1.2	13.2	18.8	1895.0	5.5	347.7	538.3
11	72131	2.284	2.302	.82	4.07	8.9	1.8	10.7	18.0	2041.7	7.5	273.3	508.3
12	72141	2.308	2.327	.85	4.85	6.9	1.9	8.8	17.8	2018.3	8.0	252.3	450.0
13	72123	2.259	2.275	.72	3.22	11.1	1.6	12.7	18.3	2836.7	6.4	445.0	641.7
14	72133	2.273	2.292	.85	4.10	10.2	1.9	12.1	18.4	2496.7	7.3	343.0	533.3
15	72143	2.304	2.327	1.05	5.05	6.6	2.3	8.9	17.9	2105.7	8.3	253.7	408.3
16	92123	2.264	2.273	.70	3.20	11.3	1.5	12.8	18.4	3756.7	8.0	474.7	733.3
17	92133	2.292	2.302	.45	3.70	9.4	1.0	10.4	17.7	3230.0	8.5	382.7	558.3
18	92143	2.304	2.317	.60	4.60	7.6	1.3	8.9	17.9	2881.7	9.7	300.0	416.7
19	11123	2.250	2.287	1.69	4.19	9.5	3.7	13.2	19.4	1710.0	6.4	272.0	466.7
20	11133	2.282	2.327	2.07	5.32	6.5	4.5	11.0	18.9	1715.0	6.7	259.7	400.0
21	11143	2.299	2.346	2.15	6.15	3.5	6.5	10.0	19.5	1408.3	6.8	209.0	383.3
22	31123	2.264	2.292	1.29	3.79	9.9	2.8	12.7	19.0	2385.7	13.5	182.7	525.0
23	31133	2.293	2.332	1.78	5.03	6.6	3.9	10.5	18.5	2173.3	8.1	270.3	491.7
24	31143	2.311	2.352	1.87	5.87	4.6	4.1	8.7	18.4	1775.0	9.8	189.0	428.3
25	71123	2.270	2.293	1.04	3.54	10.1	2.3	12.4	18.7	2981.7	7.2	417.0	591.7
26	71133	2.286	2.312	1.17	4.42	8.2	2.6	10.8	18.7	2485.7	7.0	359.0	550.0
27	71143	2.296	2.326	1.38	5.38	6.4	3.0	9.4	19.0	2240.0	7.1	317.0	516.7
28	91123	2.248	2.255	.34	2.84	12.6	.7	13.3	19.5	3815.7	8.3	454.3	783.3
29	91133	2.269	2.283	.64	3.89	9.5	1.4	10.9	19.3	3141.7	7.4	428.7	668.3
30	91143	2.294	2.314	.93	4.93	8.3	2.0	10.3	19.1	2841.7	9.3	307.3	503.3

TABLE EI, CONTD.

No.	ID	G_d	G_w	%WC_o	%TL	%V_A	%V_W	%V_T	VMA	P	F	S_m	I_m
31	12220	2.279	2.292	.59	3.09	10.9	1.3	12.2	17.9	1203.3	7.2	168.3	310.0
32	12230	2.293	2.308	.66	3.91	9.1	1.5	10.6	17.9	1250.0	8.1	156.7	295.0
33	12240	2.324	2.343	.88	4.88	6.4	2.0	8.4	17.5	1320.0	8.5	155.3	288.3
34	12221	2.271	2.293	.99	3.49	10.3	2.2	12.5	18.1	988.3	6.2	159.7	278.3
35	12231	2.294	2.320	1.18	4.43	8.0	2.6	10.6	17.9	1058.3	7.0	151.0	276.7
36	12241	2.308	2.338	1.33	5.33	6.2	3.0	9.2	18.0	938.3	8.0	119.7	238.3
37	12223	2.317	2.352	1.52	4.02	7.4	3.4	10.8	16.5	1126.7	6.0	188.7	300.0
38	12233	2.316	2.350	1.53	4.78	6.3	3.4	9.7	17.2	1101.7	8.5	130.7	237.7
39	12243	2.326	2.361	1.64	5.64	4.1	3.6	7.7	17.3	1041.7	7.5	143.0	250.0
40	12224	2.327	2.364	1.58	4.08	6.7	3.6	10.3	16.1	1050.0	6.2	170.3	288.3
41	12234	2.332	2.367	1.69	4.94	5.3	3.8	9.1	16.6	913.3	9.0	102.7	166.7
42	12244	2.326	2.370	1.96	5.96	3.9	4.4	8.3	17.4	745.0	11.2	67.0	133.3
43	32221	2.272	2.289	.76	3.26	10.8	1.7	12.5	18.1	1086.7	4.7	235.7	363.3
44	32231	2.301	2.324	1.04	4.29	8.0	2.3	10.3	17.7	1095.7	6.8	164.3	363.3
45	32241	2.326	2.353	1.18	5.18	5.6	2.7	8.3	17.4	1165.0	7.9	157.7	286.7
46	32223	2.305	2.328	1.00	3.50	8.9	2.3	11.2	16.9	1516.7	6.8	229.7	436.7
47	32233	2.323	2.349	1.13	4.38	7.0	2.5	9.5	16.9	1423.3	7.1	201.3	316.7
48	32243	2.337	2.369	1.43	5.43	4.7	3.2	7.9	17.0	1040.0	8.4	125.0	200.0
49	52221	2.256	2.271	.67	3.17	11.6	1.5	13.1	18.7	1433.3	7.3	198.0	341.7
50	52231	2.272	2.290	.82	4.07	9.6	1.8	11.4	18.7	1316.7	6.5	202.0	341.7
51	52241	2.311	2.331	.91	4.91	6.9	2.0	8.9	17.9	1315.0	8.5	154.7	276.7
52	52223	2.291	2.308	.75	3.25	10.0	1.7	11.7	17.4	1665.0	8.3	206.7	365.0
53	52233	2.317	2.337	.90	4.15	7.7	2.0	9.7	17.1	1841.7	7.8	237.7	416.7
54	52243	2.334	2.358	1.10	5.10	5.5	2.5	8.0	17.1	1475.0	9.2	161.3	250.0
55	72221	2.285	2.299	.59	3.09	10.6	1.3	11.9	17.6	1665.7	7.5	224.0	396.7
56	72231	2.311	2.329	.82	4.07	8.1	1.8	9.9	17.3	1575.7	7.4	212.3	383.3
57	72241	2.341	2.362	.94	4.94	5.6	2.1	7.7	16.8	1480.0	7.6	199.3	308.3
58	72223	2.305	2.320	.65	3.15	9.7	1.5	11.2	16.9	2158.3	8.0	271.3	466.7
59	72233	2.320	2.340	.90	4.15	7.6	2.0	9.6	17.0	1800.0	9.6	196.0	300.0
60	72243	2.332	2.355	1.05	5.05	5.7	2.4	8.1	17.2	1445.7	11.5	126.3	216.7

TABLE EI, CONTD.

No.	ID	G_d	G_w	$\%WC_o$	%TL	$\%V_A$	$\%V_W$	$\%V_T$	VMA	P	F	S_m	I_m
61	92221	2.290	2.297	.31	2.81	11.0	.7	11.7	17.4	2325.0	7.3	320.3	535.0
62	92231	2.311	2.320	.39	3.64	9.0	.9	9.9	17.3	2145.0	7.8	276.3	458.3
63	92241	2.343	2.359	.71	4.71	6.1	1.6	7.7	16.8	1980.0	8.4	234.7	400.0
64	92223	2.301	2.307	.28	2.78	10.8	.6	11.4	17.1	3178.3	8.3	383.0	600.0
65	92233	2.330	2.340	.44	3.69	8.2	1.0	9.2	16.6	2295.0	8.1	290.0	433.3
66	92243	2.326	2.343	.77	4.77	6.6	1.7	8.3	17.4	1770.0	10.8	164.3	258.3
67	11223	2.305	2.345	1.78	4.28	7.3	4.0	11.3	17.7	1498.3	6.4	235.0	391.7
68	11233	2.293	2.327	1.55	4.80	7.3	3.4	10.7	18.7	1416.7	7.2	201.7	341.7
69	11243	2.332	2.377	2.05	6.05	3.7	4.6	8.3	18.0	1083.3	9.0	120.3	225.0
70	31223	2.280	2.310	1.32	3.82	9.4	2.9	12.3	18.6	1763.3	7.2	245.0	416.7
71	31233	2.312	2.344	1.45	4.70	6.9	3.2	10.1	18.1	1655.0	8.8	188.7	383.3
72	31243	2.439	2.355	1.78	5.78	4.9	3.9	8.8	18.5	1081.7	9.9	110.0	200.0
73	71221	2.287	2.300	.59	3.09	10.8	1.3	12.1	18.4	1885.0	6.1	311.7	450.0
74	71231	2.314	2.333	.85	4.10	8.1	1.9	10.0	18.0	1955.0	7.7	256.3	475.0
75	71241	2.344	2.369	1.13	5.13	5.6	2.5	8.1	17.8	1671.7	9.4	177.3	316.7
76	71223	2.293	2.312	.84	3.34	9.9	1.9	11.8	18.1	2196.7	7.0	314.7	500.0
77	71233	2.312	2.340	1.27	4.52	7.3	2.8	10.1	18.1	1848.3	8.0	231.0	420.0
78	71243	2.339	2.370	1.41	5.41	4.8	3.2	8.0	17.7	1388.3	11.0	127.7	228.3
79	91221	2.262	2.268	.28	2.78	12.5	.6	13.1	19.3	3006.7	8.4	360.7	625.0
80	91231	2.305	2.314	.43	3.68	9.4	.9	10.3	18.3	2641.7	9.1	292.0	516.7
81	91241	2.337	2.358	.92	4.92	6.0	2.1	8.1	17.8	1838.3	9.3	202.3	391.7
82	91223	2.258	2.264	.27	2.77	12.6	.6	13.2	19.4	2933.3	8.1	362.3	616.7
83	91233	2.310	2.323	.59	3.84	8.8	1.3	10.1	18.1	2533.3	8.0	316.3	508.3
84	91243	2.328	2.347	1.05	5.05	6.4	2.3	8.7	18.2	1805.0	12.7	142.0	241.7
85	12321	2.290	2.311	.94	3.44	9.8	2.1	11.9	17.6	905.0	6.5	139.3	251.7
86	12331	2.303	2.327	1.04	4.29	7.9	2.3	10.2	17.6	1066.7	7.7	138.0	268.3
87	12341	2.307	2.337	1.34	5.34	6.1	3.0	9.1	18.1	825.0	7.7	114.7	205.0
88	12323	2.315	2.345	1.22	3.72	8.0	2.8	10.8	16.5	991.7	7.0	141.7	246.7
89	12333	2.334	2.365	1.42	4.67	5.9	3.2	9.1	16.6	1000.0	7.5	135.7	200.0
90	12343	2.335	2.370	1.59	5.59	4.4	3.6	8.0	17.1	825.0	8.8	96.3	161.7

TABLE EI, CONTD.

No.	ID	G_d	G_w	%WC_o	%TL	%V_A	%V_W	%V_T	VMA	P	F	S_m	I_m
91	32323	2.316	2.339	1.03	3.53	8.6	2.3	10.9	15.6	1405.0	8.0	183.0	331.7
92	32333	2.323	2.349	1.15	4.40	7.0	2.6	9.6	17.0	1218.3	7.8	162.0	250.0
93	32343	2.342	2.372	1.33	5.33	4.8	3.0	7.8	16.9	1200.0	9.7	124.3	211.7
94	72321	2.295	2.317	1.00	3.50	9.4	2.3	11.7	17.4	1601.7	7.1	230.7	395.0
95	72331	2.328	2.342	.66	3.91	7.9	1.5	9.4	16.8	1726.7	7.2	239.7	378.3
96	72341	2.346	2.378	1.43	5.43	4.4	3.3	7.7	16.8	1205.0	9.3	129.3	271.7
97	72323	2.316	2.328	.54	3.04	9.5	1.3	10.8	16.6	2070.0	9.7	212.7	391.7
98	72333	2.331	2.359	1.26	4.51	6.4	2.9	9.3	16.7	1705.0	8.0	192.7	291.7
99	72343	2.339	2.372	1.51	5.51	4.5	3.4	7.9	17.0	1260.0	11.3	111.7	200.0
100	92323	2.320	2.327	.31	2.81	10.1	.7	10.8	16.5	2756.7	9.1	304.0	475.0
101	92333	2.329	2.340	.43	3.68	8.2	1.0	9.2	15.7	2335.0	11.2	212.3	355.0
102	92343	2.338	2.353	.67	4.67	6.4	1.5	7.9	17.0	1631.7	12.2	134.0	191.7
103	11323	2.303	2.337	1.53	4.03	8.2	3.4	11.6	17.9	1145.0	6.6	173.3	316.7
104	11333	2.314	2.353	1.76	5.01	6.2	3.9	10.1	18.1	926.7	7.5	127.3	233.3
105	11343	2.336	2.384	2.15	6.15	3.4	4.8	8.2	17.9	735.7	8.5	87.0	140.0
106	31323	2.285	2.308	1.03	3.53	9.9	2.3	12.2	18.5	1453.3	7.2	200.7	350.0
107	31333	2.327	2.366	1.72	4.97	5.7	3.8	9.5	17.6	1370.0	8.8	155.3	291.7
108	31343	2.333	2.375	1.73	5.73	4.3	3.9	8.2	17.9	771.7	11.3	69.3	141.7
109	71323	2.283	2.297	.67	3.17	10.8	1.5	12.3	18.6	1918.3	8.3	238.3	445.0
110	71333	2.323	2.344	.93	4.18	7.6	2.1	9.7	17.8	1690.0	8.4	201.3	341.7
111	71343	2.354	2.384	1.35	5.35	4.5	3.0	7.5	17.3	1180.0	11.2	105.7	211.7
112	91323	2.306	2.314	.36	2.86	10.6	.8	11.4	17.8	2953.3	8.5	350.0	616.7
113	91333	2.330	2.345	.67	3.92	7.9	1.5	9.4	17.5	2180.0	11.8	186.0	348.3
114	91343	2.340	2.359	.89	4.89	5.6	2.7	8.3	18.0	1388.3	16.0	87.3	170.0

TABLE E2, Summary of Water Sensitivity Test Results

Notes:

(1) - The reduced data are the average of the duplicate specimens tested for each mix combination.

(2) - All the response parameters symbols are defined in the "list of symbols".

(3) - The ID number that identifies each data set is the same as was explained in table E1.

TABLE E2, CONTD.

No.	ID	%MA	%P	%Sm	%Im
1	12133	2.71	43	47	49
2	12223	2.59	41	57	50
3	12233	1.88	58	67	68
4	12243	1.13	57	48	44
5	12333	2.07	37	37	33
6	32133	3.06	51	55	66
7	32223	3.17	69	67	63
8	32233	2.31	73	56	63
9	32243	1.26	81	66	69
10	32333	2.26	72	81	92
11	92133	1.35	86	81	88
12	92223	2.46	69	62	66
13	92233	1.88	106	82	98
14	92243	1.28	106	88	116
15	92333	2.23	73	63	65
16	11133	1.71	87	85	92
17	11223	2.11	81	83	89
18	11233	1.69	81	77	88
19	11243	.89	75	63	62
20	11333	1.43	93	86	94
21	31133	1.56	80	81	79
22	31223	2.57	92	101	96
23	31233	2.04	84	77	80
24	31243	1.37	79	69	63
25	31333	2.14	100	99	80

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